OARDC Special Cir. 102
Extension Bul. 651
November, 1979

CONSERVING ENERGY IN OHIO GREENHOUSES

Cooperative Extension Service ★ The Ohio State University
Columbus, Ohio
Ohio Agricultural Research and Development Center
Wooster, Ohio

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Conserving Energy in Ohio Greenhouses

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The production of greenhouse crops, with sales totalling more than $80 million annually, is an important part of Ohio's agriculture. Unfortunately, inflation has been particularly hard on greenhouse growers. Their production costs have increased much more rapidly than product market prices. And the cost of energy, particularly for greenhouse heating, has been one of the most rapidly rising expenses. In order to make the most profit, then, growers must use energy efficiently.

The first step to efficient energy use should begin with the proper design and construction of the greenhouse structure and installation of the heating system. Second, the equipment and structure need to be properly maintained to retain efficient energy use and promote long life.

The third step is to modify the structure or heating system by using newly developed methods that increase efficiency over and beyond the original design. Most of these involve techniques to increase greenhouse insulation. In the past, the need for good light transmission limited attempts to insulate greenhouse structures. But new methods allow greenhouse insulation that 1) retains all or most of the light transparency or 2) are opaque and are used only at night when light is not a factor, and the heating need is the greatest.

Using common sense cannot be overemphasized when changing greenhouse practices to include energy-conservation measures. Creating a tighter, more energy-efficient greenhouse will result in higher humidities and require changes in watering, ventilation, and disease prevention practices. A tight structure will keep the energy inside, but it will cut off the major source of CO_2 from the outside. CO_2 depletion, if not corrected, may result in reduced yields and quality or delayed maturity. Insulating the greenhouse may reduce the total light reaching the crop and result in similar production problems. The movement and storage of objects such as thermal blankets may reduce total greenhouse bench space and may also eliminate production area for hanging crops.

To compound these problems, an energy-efficient structure maintains a warmer and more uniform environment that may delay some crops, advance others, and increase yields of other crops.

In summary, installing an energy-conservation measure does not mean that management can relax. In some instances, the manager may have to relearn or review basic horticultural principles, so that he may successfully grow in this "new" environment. But if he can meet these challenges, and this handbook will demonstrate how, together with using common sense in making decisions about his operation, he can save considerable amounts of energy and money.

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The authors, Phillip C. Badger, former research associate, agricultural engineering, and Hugh A. Poole, assistant professor, horticulture, express appreciation to Ted H. Short, associate professor of agricultural engineering, William L. Bauerle, associate professor of horticulture, and Priscilla Gresser, technical assistant, Department of Horticulture, Ohio Agricultural Research and Development Center, and The Ohio State University, for their assistance in the preparation of this manuscript.

This publication was prepared and funded through a cooperative effort of the Ohio Department of Energy, the Ohio Agricultural Research and Development Center, and the Ohio Cooperative Extension Service.

1 basics of management

Heat Transfer

Heat transfer is an energy exchange process in which many modes of exchange can occur simultaneously. To simplify, heat transfer is usually broken down into these three categories, and each is evaluated separately:

Conduction — heat transfer occurring either through a substance or between objects by direct physical contact of the objects (Fig. 1.A.1.). The rate

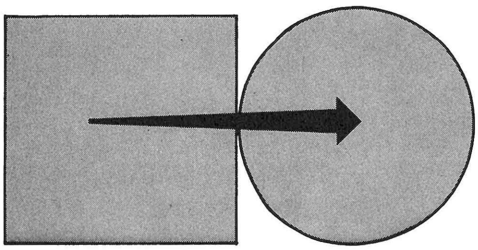


Fig. 1.A.1. Conduction heat transfer. Objects are in contact.

of conduction depends on the area, path length, temperature difference and the physical properties of the substance, such as its density. Heat transfer by conduction can be reduced by replacing a good thermal conductor with a poor thermal conductor (insulator) or by placing an insulator in the heat flow path. An example of this would be replacing a kitchen pan's metal handle with a wooden handle or insulating the metal handle by covering it with wood.

Radiation — heat transfer occurring between two bodies without direct contact and without the need for an intervening transporting medium (Fig. 1.A.2.). Just as light does, heat radiation follows a straight line path and is either reflected, transmitted or absorbed upon striking an object. Radiant energy must be absorbed to be converted to heat.

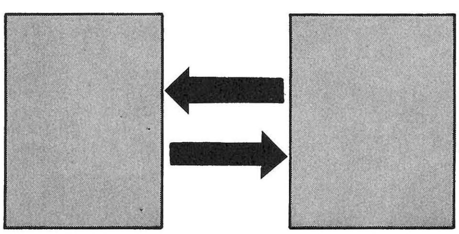


Fig. 1.A.2. Radiation heat transfer, Objects are separated.

All objects give off heat in all directions in the form of radiant energy, and all objects vary in their capacity to absorb and give off (emit) radiation. The rate of radiation heat transfer varies with the areas, temperatures, and surface characteristics of the two bodies involved (objects). Based on its surface characteristics, an object is rated in terms of its ability to emit radiation on a scale of zero to one (nothing emitted to everything emitted). Thus, an emissivity rating close to one indicates that the object will readily give off (emit) energy.

It has been shown experimentally that objects which are good emitters of radiation are, in similar circumstances, also good absorbers of radiation. Thus, the zero to one emissivity rating may also be thought of as an absorber rating of the surface. Objects with an emissivity rating close to zero are poor absorbers and poor emitters of radiation. Generally, highly reflective surfaces are poor absorbers and poor emitters of radiation while black surfaces are good absorbers and good radiators. Emissivity ratings are frequently used to designate the effectiveness of thermal blanket materials.

Taking these principles into account, heat losses from an object by radiation can be minimized by surrounding the object with a highly reflective opaque barrier. Such a barrier:

1. Reflects the radiant energy back to its source;
2. Reduces absorption by the barrier and reradiation of energy to objects beyond the barrier;
3. Prevents transmittal of radiation, thus preventing objects from "seeing" each other, which is necessary for radiant energy exchange to occur.

Convection — heat transfer by movement of warm gas or liquid to a colder location (Fig. 1.A.3.). Greenhouse heat losses by convection occur through ventilation and infiltration. Ventilation is air movement through controlled openings and may be forced or natural. Infiltration is natural air movement through cracks and openings in the greenhouse surface. Heat transfer by convection can be minimized by placing barriers in the flow path to prevent the mass movement.

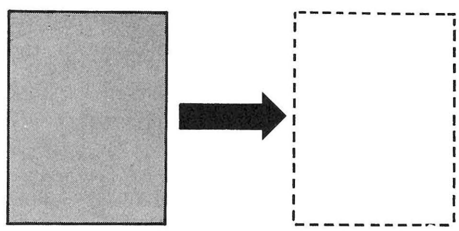


Fig. 1.A.3. Convection heat transfer. Warm material moves to a colder location.

Heat transfer by convection includes not only the movement of a warm mass from location to location but also the movement of water vapor. When water in the greenhouse is evaporated into vapor, energy is absorbed in the process. When that water vapor is condensed back into a liquid, energy is given up. Thus, water vapor is an energy carrier. When condensation occurs on the roof, the released energy is conducted through the roof and lost to the outside. Also, relative humidities in the greenhouse are usually higher than those outside, so when air is exchanged by ventilation or infiltration and water vapor is lost, energy is also lost.

Heat Loss Calculations

It is useful to know some heat loss calculation procedures to predict heating loads and identify areas of the greenhouse with the most heat loss. Heat loss by conduction may be calculated with the following equation:

$$Q = U\,A\,(Ti - To)$$

where

Q = heat transfer rate, Btu/hr.

U = heat transfer coefficient, Btu/hr.-ft.^{2}-°F

A = surface area, ft.^{2}

Ti-To = air temperature difference between inside and outside, °F.

Sometimes "R" values (the resistance to heat flow) are listed instead of "U" values. The relation between "U" and "R" is:

$$U = \frac{1}{R}$$

The conduction heat transfer equation using "R" can then be written as:

$$Q = \frac{A(Ti-To)}{R}$$

Frequently it is more convenient to work with "R" values when dealing with insulation, as the added effect of insulation can be determined quickly by simply summing the "R" values of materials in the heat flow path. For example, from Table 1.B.1., the "R" value for a single layer of glass is equivalent to 0.88 and for 1-inch-thick styrofoam, 4.00. Adding styrofoam to a single-layer glass surface will give the wall an insulation value of R = 0.88 + 4.00 = 4.88 (or a "U" value of 1/4.88 = 0.204). Note that high "R" values and low "U" values indicate less heat flow.

Returning to the conduction heat transfer equation, we can reduce "Q," the heat transfer rate, by: 1) decreasing the amount of area for heat transfer, 2) decreasing the temperature difference between inside and outside, or 3) substituting or adding a material with a higher "R" value (lower "U" value). The first two methods listed are difficult to apply to exist-

TABLE 1.B.1. Heat Transfer Coefficients for Construction Materials.

Material	R value ** (hr. °F sq. ft./Btu)
1. Glass, single layer	0.88*
2. Glass, double layer, ¼ in. space	1.54*
3. Glass, triple layer, ¼ in. space	2.13*
4. Clear polyethylene film, single layer (2,4, or 6 mil)	0.87*
5. Clear polyethylene film, double layer, separated (2,4, or 6 mil)	1.43*
6. Polyethylene film, double layer, separated over glass	2.00*
7. Fiberglass	1.00*
8. Double acrylic (Acrylite SDP™)	1.78*
9. Double polycarbonate (Tuffak-Twinwal™)	1.61*
10. Face brick, 4 in. thick	0.44
11. Concrete block, 8 in.	1.96
12. Concrete block, 8 in. plus 1 in. foamed urethane	7.69
13. Concrete block, 8 in. plus 1 in. foamed polystyrene	5.55
14. Concrete, poured, 6 in.	1.33
15. Cement asbestos board, ¼ in.	0.91
16. Cement asbestos board, ¼ in. plus 1 in. foamed urethane	7.14
17. Cement asbestos board, ¼ in. plus 1 in. foamed polystyrene	4.76
18. Microfoam™, ¼ in. thick	1.08
19. Polystyrene (beadboard or loose fill), ½ in. thick	2.10
20. Polystyrene (beadboard or loose fill), ¾ in. thick	3.05
21. Polystyrene (beadboard or loose fill), 1 in. thick	4.00
22. Extruded polystyrene (Styrofoam™), 1 in. thick	5.40
23. Polyurethane foam (applied at site), 1 in. thick	7.30
24. Plywood ½ in.	0.62
25. Plywood 1 in.	1.25
26. 1 in. nominal softwood	1.79
27. Expanded vermiculite (4-6 lb./cu. ft., 1 in. thick)	2.20
Curtain Materials	
28. Al/Temp,™, aluminum down	1.43
aluminum up	1.18
29. Al/Blac™	1.37
30. Duracote #2425 (Foylon™)	2.63
31. Black Sateen	1.54
32. Black poly, 6 mil	1.05
33. Reemay™, spunbound polyester, 2016	0.83
34. Vinyl (aluminized polyester laminated vinyl) 4.5 mil	2.15

** The R value represents the resistance to heat flow at the thickness listed. The higher the R value the better the insulating property.

* Includes effects of surface coefficients.

Acrylite S.D.P., TM CY/RO Industries
Al/Blac, TM Simtrac, Inc.
Al/Temp, TM Simtrac, Inc.
Foylon, TM Duracote Corp.
Microfoam, TM DuPont
Reemay, TM DuPont
Styrofoam, TM Dow Chemical
Tuffak-Twinwall, TM Rohm and Haas Co.

ing greenhouse situations because the outside surface area of the greenhouse is fixed, and the outside air temperature is uncontrollable. The only way to decrease the temperature difference is to decrease the inside air temperature. This method is discussed in a separate publication dealing with cultural factors. The easiest way to reduce the conduction heat transfer rate is to substitute or add a material with a higher "R" value into the heat flow path.

Different materials commonly used in greenhouse construction and their associated "R" values are listed in Table 1.B.1. These values are relatively fixed at ordinary temperatures unless the materials are permeable to water vapor. The absorption of water will reduce the "R" value and speed up the heat transfer process. The extent of insulation loss will depend on the properties of the material and the amount of water absorbed. The value of the insulation becomes minimal, if the water can fill the tiny air spaces that provide the insulation effect.

Infiltration heat losses can be significant and should be calculated and added to conduction heat losses. The equation for infiltration heat transfer (Btu/hr.) is: Q = 0.02 x (Ti-To) x (greenhouse volume, ft.^{3}), x (number of changes per hour). As shown in Table 1.B.2., the number of air exchanges per hour will vary depending on the type and condition of the greenhouse and the amount of wind.

TABLE 1.B.2. Natural air exchanges for greenhouses.

Construction system	Air exchanges per hour*
1. New construction, glass or fiberglass	0.75 to 1.5
2. New construction, double layer plastic film	0.5 to 1.0
3. Old construction, glass, good maintenance	1 to 2
4. Old construction, glass, poor condition	2 to 4

*(low wind or protection from wind reduces the air exchange rate.)

Once dimensions are known and listed, the areas and volumes can be calculated with the following equations for the appropriate greenhouse style:

Single gable greenhouse (Fig. 1.B.1.)

Wall area = 2(FxC)

End area = (2xFxB)+(GxB)

Roof area = 2(DxC)

Foundation area = 2(ExC) + 2(ExB)

Volume = AxBxC + 1/2 (BxG)xC

Gutter-connected gable greenhouses
(N = number of greenhouses)
(Fig. 1.B.2.)

Wall area = 2(FxC)

End area = $[2(FxB) + \frac{2(GxB)}{2}] \times N$

Roof area = [2(DxC)] x N

Foundation area = 2(ExC) + [2(ExB) x N]

Volume = [AxBxC + 1/2 (BxG) x C] x N

Gutter-connected, curved-roof greenhouses
(N = number of greenhouses)
(Fig. 1.B.3.)

Wall area = 2(AxC)

End area = 2[2/3 (HxB) + (AxB)] x N

Roof area = (DxC) x N

Volume = [2/3 (HxBxC) + (AxBxC)] x N

Quonset-style greenhouse (Fig. 1.B.4.)

End area = 4/3 (HxB)

Roof area = DxC

Volume = 2/3 (HxBxC)

To calculate heat loss from a greenhouse:

1. Calculate infiltration (Q_I)

   Q = 0.02 x (Ti-To) x Volume x Air Exchange (Table 1.B.2.)

   □ = 0.02 × □ × □ × □

2. Calculate conduction (Q_C)

	A (Area)	"R" Value (Table 1.B.1.)	$Q_C = \frac{A\ (Ti\text{-}To)}{R}$
Wall			
End			
Roof			
Foundation			
		Total Q_C =	

3. Calculate total heat loss

   $Q_T = Q_I + Q_C$

   □ = □ + □

For example, calculate the heat loss from six gutter-connected glass gable greenhouses (covering about ¼ acre) with dimensions in feet as shown in Fig. 1.B.2.

A = 8
B = 20
C = 90
D = 11.18 (11 ft. - 2 in.)
E = 2
F = 6
G = 5
N = 6

The houses are of old construction, in poor condition, and exposed to little or no wind for the time in question. The house foundation is constructed of six-inch poured concrete. The inside greenhouse air temperature is to be maintained at 60°F, and the outside air temperature averages 20°F.

SOLUTION: From Table 1.B.1., the "R" value for a single layer of glass is 0.88, and for six inches of poured concrete the "R" value is 1.33. From Table 1.B.2., the number of air exchanges per hour would be approximately two, based on these house and wind conditions. The temperature difference between inside and outside (Ti-To) is equal to 60°F minus 20°F or 40°F.

Calculate the areas and volume using the formulas for gutter-connected gable greenhouses listed previously:

Wall area
= 2x(FxC)
= 2(6x90)
= 1080 sq. ft.

End area
= [2x(FxB) + (GxB)] x N
= [2(6x20) + (5x20)] 6
= 2040 sq. ft.

Roof area + [2x(DXC)]xN
= [2x(11.18x90)]x6
= 12,074 sq. ft.

Foundation area
= 2 (ExC) + [2(ExB)xN]
= 2(2x90) + [2(2x20)x6
= 840 sq. ft.

Volume
= [(AXBXC)+1/2 (BXG)xC]xN
= [8x20x90 + 1/2 (20x5) x90] x 6
= 113,400 cu. ft.

Calculate heat loss by conduction (Qc) for each area; in this case

$$Qc = \frac{(\text{Area}) \times (40°F)}{R}$$

	Area	"R"	Qc
Wall	1,080	0.88	49,090
End	2,040	0.88	92,727
Roof	12,074	0.88	548,727
Found.	840	1.33	25,263
		Total	715,807 Btu/hr.

Calculate heat loss by infiltration (Q_I):

Q_I = 0.02 x 40 x 113,400 x 2 = 181,440 Btu/hr.

Total heat loss for the greenhouse under the conditions given is the sum of infiltration and conduction heat losses:

$Q_T = Q_I + Qc$
= 181,440 + 715,807
= 897,247 Btu/hr.

Factors Affecting Heat Losses From Greenhouses

Because different materials have different heat transfer properties, the type of greenhouse construction can affect heat loss (Fig. 1.C.1.) For example, metal greenhouse frames conduct heat better than wood frames. Coverings of double layers of plastic reduce conduction heat loss by providing a dead air space which is insulation.

The rate of heat loss by infiltration depends on the age, condition and type of greenhouse. Even glass greenhouses in good condition allow infiltration through openings at the glass laps. Older greenhouses or ones in poor condition generally

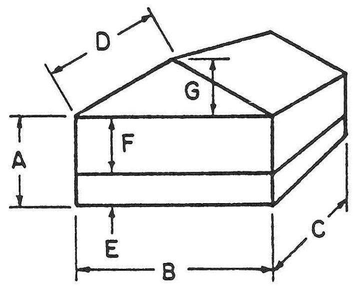


Fig. 1.B.1. Single gable greenhouse.

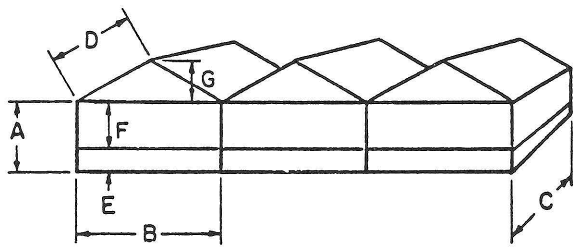


Fig. 1.B.2. Gutter-connected gable greenhouses.

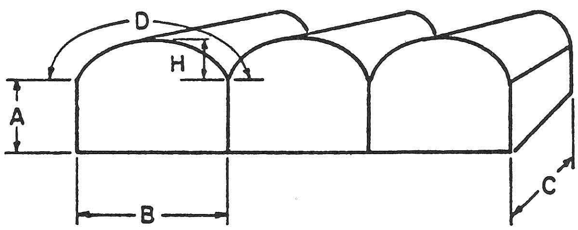


Fig. 1.B.3. Gutter-connected, curved-roof greenhouse.

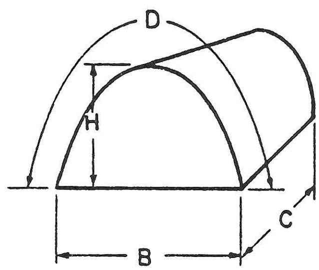


Fig. 1.B.4. Quonset-style house.

have cracked, slipped, or missing glass and excessive cracks at glass laps. Using larger glass panes or large sheets of fiberglass will reduce infiltration. Greenhouses covered with single or double layers of plastic will have the least amount of infiltration.

The amount of radiation heat loss depends on the type of external cover on the greenhouse. Fiberglass and glass materials allow less than four percent of the thermal radiation to pass through, in contrast to 70 percent for polyethylene. However, a small amount of condensation on the polyethylene can reduce this thermal transmittance to 50 percent, and heavy condensation can reduce it further to 25 percent.

Radiation heat transfer occurs between the sky and the plants inside the greenhouse or the greenhouse cover. Because an important factor controlling radiation heat transfer is the temperature difference between "objects," cloudy condi-

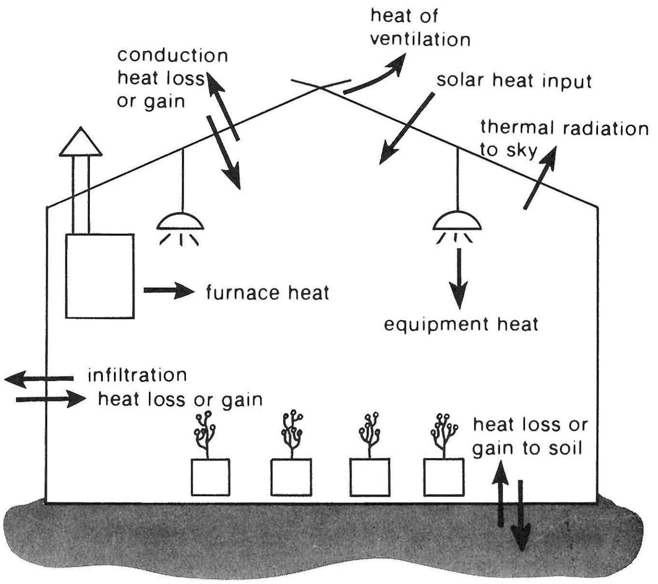


Fig. 1.C.1. Modes of heat exchange between the greenhouse and surroundings.

tions reduce radiation losses by providing a warmer "object" to receive radiation than the clear sky.

Other heat loss factors are also important. Small greenhouses have more surface area relative to the volume enclosed and are more difficult to heat. Corrugated fiberglass on the greenhouse exterior may undesirably increase the heat transfer surface area. For example, corrugated fiberglass has nine to 26 percent more surface area than flat fiberglass. Tall crops, such as tomatoes, intercept and absorb more light than low crops, such as lettuce. However, tall crops also provide more surface for reradiation of energy. These crop effects are more significant in single houses than in gutter-connected or wide-span houses.

2 methods of conservation

Most conservation methods can be grouped as either modification or maintenance techniques. A few methods, also important, fit into a miscellaneous category. Modification and maintenance methods apply both to the structure and the heating system. Structural modifications usually reduce infiltration and add insulation to the greenhouse. Heating system modifications seek to optimize the recovery of heat from the burned fuel.

The energy conservation methods to follow are listed for ease in gathering important cost and fuel savings information. The potential savings listed are annual savings and will vary with location, type and condition of greenhouse. Actual savings over a given time and with certain weather conditions can run much higher.

Consider combined systems with caution. Adding the potential savings listed for two systems will not necessarily indicate the total expected savings, if both methods are used. For instance, if the addition of double plastic or a curtain system to a greenhouse will provide a 50 percent fuel savings each, adding both to the greenhouse will not give a 100 percent fuel savings. This is true because part of the heat flow that the double poly would have stopped has already been stopped with the curtain system.

This example also demonstrates another pitfall. Not all systems listed are economically compatible. In the preceding example, if both systems had been installed in a greenhouse, the amount of heat saved by one system would jeopardize the economics needed to justify the investment in the other system.

The following summary (Table 2.1) of engineering conservation methods is based on the standard glass greenhouse as a reference. The "continuous" methods are in use 24 hours a day while the "periodic" methods are used only for nighttime insulation. The actual annual savings realized will vary with greenhouse and weather conditions. It is possible with ideal conditions to observe savings greater than those listed. Use care when evaluating figures for unknown conditions, especially if based on short time intervals.

TABLE 2.1. Summary of potential annual savings for energy conservation methods.

METHOD	Annual % Saving Range
O. Glass	0 (base)
A. Major Modifications	
Continuous	
1. Double plastic film over glass	40-60
2. Glass lap sealants	5-40
3. Single plastic film over glass	5-40
4. Double layer plastic film	30-40
Periodic	
5. Curtains	20-60
6. Polystyrene pellets	60-90
7. Liquid foam	40-75
B. Other Modifications	
1. Sidewall insulation	5-10
2. Foundation insulation	3-6
3. Insulating ventilation fans	1-5
4. Heating systems	
a. Automatic firetube cleaners	6-20
b. Turbulators	8-16
c. Stack heat recovery unit	?
C. Maintenance	
1. Structure	3-10
2. Heating system	10-20
D. Miscellaneous Factors	
1. Windbreaks	5-10
2. Greenhouse orientation	5-10

3 maintenance methods

Maintenance procedures seek to preserve the maximum designed operating conditions of the heating system and structure. While maintenance procedures usually provide less savings than modification methods, they usually are easier to do and require a smaller investment. Proper maintenance will also prolong the life of the structure and equipment and insure against failure during critical crop periods.

When possible, use summer downtime to inspect and overhaul the heating system. Properly designed, installed, and maintained systems will distribute more uniform heat resulting in a lower thermostat setting and better plant growth.

Most important: inspect the equipment and structure regularly and make repairs or adjustments as soon as possible. Every tool and piece of equipment was designed for a particular purpose, and detailed instructions for proper use are printed by the manufacturer. These instructions should be filed in a safe place and studied periodically to ensure efficient equipment use.

Maintenance Technique Structural Maintenance

Potential Savings — 3 to 10 percent annually

Possible Action —

Proper maintenance of the greenhouse structure will minimize infiltration heat losses. Heat is lost during infiltration because:

1. Warm air must move out of the greenhouse to make room for infiltrated air,
2. The cold incoming air must be heated to greenhouse temperature,
3. Water vapor, an energy carrier, is lost with the warm air leaving the greenhouse.

To minimize infiltration, fix broken or slipped glass and patch torn plastic. Also, caulk foundation cracks, add weatherstripping and door closers to doors and make sure vents close properly (Fig. 3.A.1.). Add a second door to form an airlock buffer zone between doors that go directly outside and are frequently used.

During winter, keep greenhouse glazing clean to allow maximum transmission of solar energy to decrease the heating load and increase plant growth.

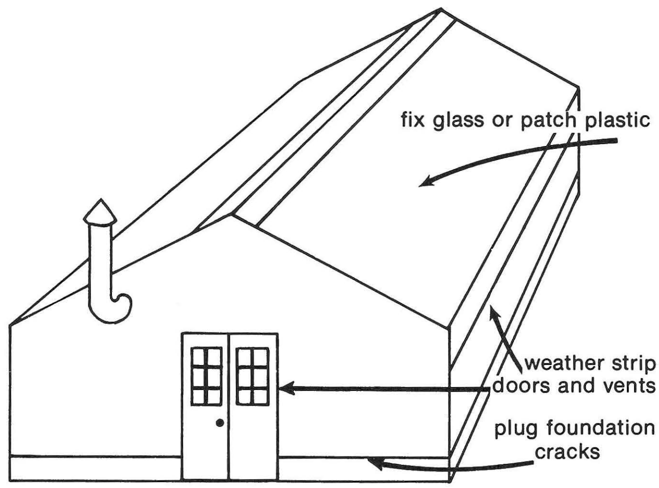


Fig. 3.A.1. Maintaining the greenhouse structure.

Maintenance Technique Heating and Ventilating System Maintenance

Potential Savings — 10 to 20 percent annually

Possible Action —

Fuel

Use the proper fuel for your heating unit. The wrong grade or type of fuel can cause soot accumulation and reduce heat transfer.

Buy clean fuel and protect it from dirt. Fuel storage tanks should have dust-free locations and watertight fittings. Change oil filter screens regularly. Inspect fuel lines for leaks.

Use the correct nozzle size and angle. Excessive fuel consumption will result from too large or too small a nozzle. The spray angle should fit the shape of the fire box.

Clean and adjust boiler or heater controls. Check gas valves, thermostats, and ignition mechanisms for clean, smooth operation.

Heating Units

Check boiler efficiency to insure optimum performance. Fuel-to-steam efficiency depends on the temperature of the exhaust gases leaving the boiler and burner effectiveness. A low stack temperature indicates good heat exchange and less heat flow up the stack. Consistently high CO_2 levels with no CO and low oxygen levels indicate a good burner and a good air-fuel ratio control.

Kits for measuring flue gases are relatively inexpensive and available from heating, ventilating, refrigerating supply houses. Directions come with the kits. Further help may be obtained from the boiler manufacturer.

However, some growers may not be making wise use of their time by doing their own boiler testing and adjusting. Most growers start off with good intentions, but too frequently they put off the job until "time is available." Either time never becomes available, or not enough time is allowed to do a proper job. Hiring reputable outside firms assures the job will be done properly and regularly. Using a firm with the equipment and training necessary to do the job quickly and efficiently will represent money well spent.

Probably the best approach is to have the boiler annually inspected, cleaned and adjusted by a qualified serviceman. After the unit is properly adjusted, the grower can periodically (at least monthly) check and record the stack temperature. An increase of 50°F indicates possible problems. The grower should also check his fuel bill monthly. Any increase beyond normal heating requirements for that time of year signifies a problem and the need to call qualified help. (Your fuel supplier can help you determine normal fuel requirements.) Keep a record of furnace maintenance and repairs for future reference.

Providing Adequate Combustion Air for Unit Heaters or Central Boilers

In plastic film houses and tight glass and fiberglass houses, install a louvered air intake from outside to near the heating unit (Fig. 3.B.1.). *Do not* connect directly to the heating unit, as air gusts may extinguish

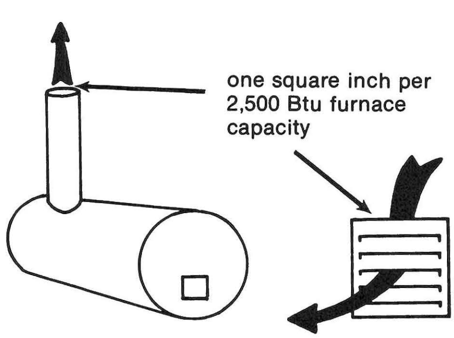


Fig. 3.B.1. Provide combustion air and sufficient chimney size.

the pilot, and cold air will reduce heater efficiency. Allow one square inch of louvered air inlet area from outside for each 2,500 Btu of furnace capacity. If the manufacturer does not state the free area of a louver, or the louver in question is of unknown origin, there are two rules of thumb to determine the free area. The first is wooden louvers have 20 percent free area. The second is metal louvers have 60 percent free area when open.

Inadequate combustion air will prevent complete combustion and proper venting of combustion gases. The products of incomplete combustion may be discharged into the greenhouse from the draft diverter on the heater. The unburned gas, carbon monoxide, and other chemical gases may create an unsafe environment for plants and workers.

Incomplete combustion causes soot buildup which reduces heat transfer and lowers heater efficiency.

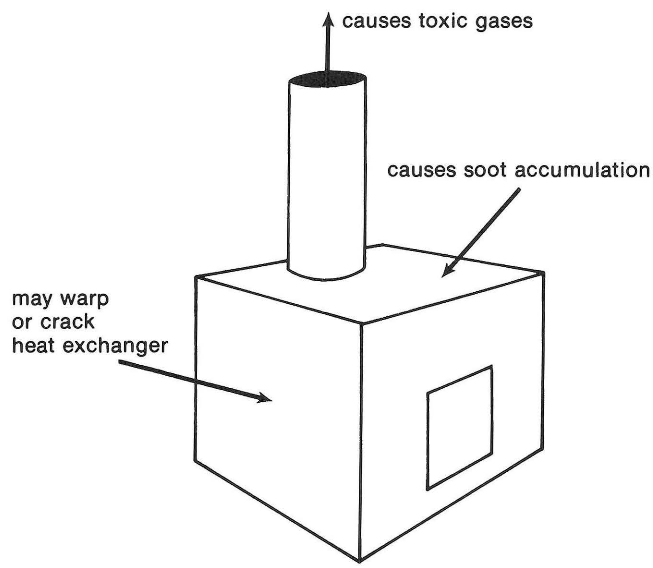
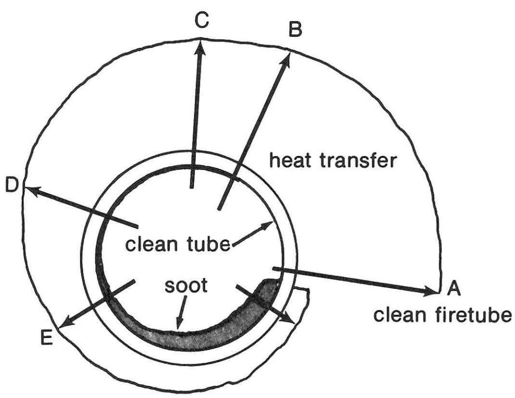


Fig. 3.B.2. Incomplete combustion.

(Fig. 3.B.2.). A one-eighth inch soot deposit can increase fuel consumption as much as 15 percent (Fig. 3.B.3.). Surfaces should be wire brushed and vacuumed or special cleaning compounds used. Follow manufacturer's instructions. Incomplete combustion may cause unstable flames which burn directly on the heat exchanger material and causes the heat exchanger to warp or crack prematurely.

If the boilers are in a separate enclosure, the waste heat off the boilers may be used to heat combustion air and decrease soot buildup. Trap boiler room waste heat by keeping the combustion air inlets low in the



Firetube heat transfer diagram

Fuel Loss Because of Soot

	Thickness of soot in firetubes	Loss of efficiency in firetubes	Average fuel loss
A	0"	0.0%	0.0%
B	1/32	9.5	2.9
C	1/16	26.2	7.8
D	3/32	35.7	10.7
E	1/8	45.3	13.6
F	3/16	69.0	20.7

Fig. 3.B.3. Effect of soot on firetube heat transfer.
Fuel Efficiency, Inc., Newark, N.Y.

structure. Excessive heat off boilers can be reduced by insulating the boiler jacket. Another way to get full use of boiler heat is to install them in the greenhouse itself.

Keeping Heating System Water Clean

Drain off dirty water through drain cock in steam and hot water systems. Flush steam boilers to remove scale and lime deposits. Maintain a regular check on water mineral content and pH and provide corrective chemicals as needed. Most suppliers of water treatment chemicals will provide this service free, if you use their chemicals. Depending on water mineral content, pretreatment of water may minimize the need for chemicals.

Chimney

Check chimney height. It should extend at least two feet above the ridge of the greenhouse. The top of the chimney should be at last eight to 12 feet above the furnace to develop sufficient draft. Tall stacks allow for distribution of exhaust gases before the gases reach the ground level. This prevents pollution injury to plants from incoming ventilation or infiltration air. Use a chimney cap to prevent back drafts that could cause air pollution injury to plants.

Chimney and Furnace Tightness

Chimney air leaks will chill the gases and reduce the draft. Pollution from furnace and chimney leaks may also injure plants. Check furnaces and chimney tightness with a furnace candle. These candles burn for about a minute and give off a dense yellow smoke. Shut off the furnace, cover the draft damper inlet (if any), insert the lighted candle and watch for the dense yellow smoke. Wait 30 seconds and if smoke is not visible, turn on the circulating fan and watch for smoke in the heat distribution system. If smoke is still not visible, fire up the furnace and watch for the dense yellow smoke at cracks or leaks in the chimney.

Draft Regulation

Too small a cross-section or a chimney lined with soot will reduce the draft. Too large a diameter will cool the gases too quickly. Allow one square inch of duct cross-section for each 2,500-Btu heater capacity.

Draft control is necessary to promote even and efficient burning. Draft variations because of atmospheric conditions can be stabilized by installation of a draft regulator.

Heat Distribution System

Check all heating lines, valves, and check valves for leaks and proper operation while the heating system is operating. Each pound of steam leaked loses 1,500 Btu. A 1/16-inch diameter hole in a steam line can waste as much as seven gallons of fuel daily. Valves may need new seats or gaskets. All sediment traps, thermostatic and/or bucket traps should be inspected and cleaned. All return pumps and their circulating equipment should be checked as well as thermometers, pressure gauges, air-escape valves, and pressure regulators. Oil bearings on motors and pumps as manufacturer instructs.

Check the blower timing in forced-air systems. Blowers should operate until furnace is cooled to 100°-120°F, or continuously when desired.

Dust and dirt reduce heat transfer and increase fuel consumption. Paint heating pipes and radiators to prevent rusting. Use any type of paint except metallic, such as aluminum.

Insulate pipes in unheated areas, underground or wherever heat is not needed. A one-foot section of uninsulated six-inch pipe, with a 150°F temperature difference between inside and outside can waste more than 600 Btu per hour or one gallon of No. 2 fuel oil per hour for every 225 feet of pipe. Each pound of steam condensed before reaching the greenhouse loses 1,200 Btu.

Control System

Check furnace and ventilation fan thermostat setting. Set ventilation fan thermostat at least 10°F above heater thermostat to prevent wasteful simultaneous operation and possible furnace back-draft. Heating and cooling thermostats may also be electrically interlocked to prevent simultaneous operation.

Make sure the greenhouse thermostats give representative readings. Thermostats located on a cold wall, in the sun, or without air movement over them do not allow representative temperature readings. Ten percent more fuel is required to maintain a greenhouse at 62°F instead of 60°F, if the outside temperature is 40°F.

Mount all control thermostats in ventilated, white-painted wood boxes or similar containers with a maximum/minimum thermometer for calibration (Fig. 3.B.4.). Locate the box centrally in the greenhouse at

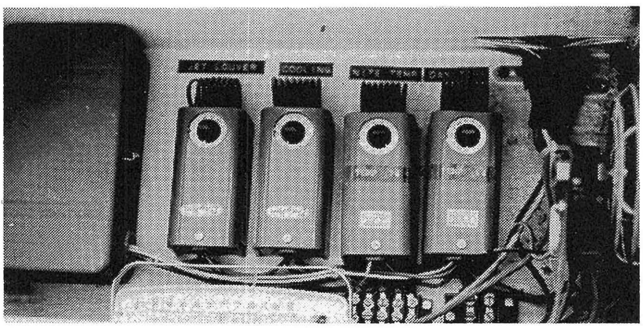


Fig. 3.B.4. Aspirated thermostat control box.

plant level away from walls and heaters. Make sure the aspirating fan blows out of the box, *not* into the box, to avoid effects of motor heat. The fan motor should be totally enclosed to protect it from greenhouse dust. Check the fan periodically throughout the season to assure it is working.

Periodically use a maximum/minimum thermometer or thermograph (recording thermometer) to check the accuracy of the thermostat over at least a 24-hour period. Ideally, the thermometer should be mounted beside the thermostat. Replace thermostats that produce widely varying temperatures provided that heating/ventilating control circuits and valves are operating correctly. Thermostats producing temperatures that vary consistently from the set temperature can be adjusted to compensate for the off-reading.

Also, calibrate the thermometer at least yearly by placing it in ice water for a period of time. Replace if inaccurate, or if the mercury has separated, or if maximum/minimum-indicating indices have slipped down into the mercury.

Inspecting and Maintaining Fans and Louvers

Check fans, motorized shutters, and the control system for proper operation. Check fan and motor bearings for overheating; lubricate or replace as required. Check pulley sheaves for correct alignment. Shafts should be parallel, and edges of sheaves should line up with a straight edge. Check V-belts for proper tension by "striking" the belt with the fist. Slack V-belts feel dead under this test, while properly adjusted V-belts vibrate and feel alive and springy. Slack belts wear excessively, cause slippage, deliver less power, and may cause belt breakage. Excessive tension can cause bearing wear and possible failure. Belts should be kept clean, free of oil, and protected from sunlight as much as possible. Mineral oil is especially destructive. For normal cleaning, belts should be wiped with a dry cloth. The safest way to remove excessive dirt and grime is to wash with soap and water and rinse well. Belt dressing should never be used on a V-belt drive.

Remove dust accumulations from fans, housings, and shutters to prevent fan vibration and to provide an unobstructed air flow. Excessive fan vibration will reduce air flow and stress the bearings. Check unmotorized pressure louvers for free operation and tightness of seal when closed. Remove weeds and shrubs growing outside the greenhouse that block fans and interfere with louver operation.

Check fans for proper rotation. Fans can be accidentally reversed by switching wiring during repairs or modifications. Reversed fans will move some air and may not be readily detectable.

4 modification methods

In comparison with maintenance methods, modification methods generally cost more and are difficult to implement but save more energy. Structural modifications that reduce infiltration cause increased humidities and may cause depressed levels of CO_2 unless CO_2 is supplemented. Also, some modification methods may cause a light reduction or heavy spot shading. The grower should be aware of these potential problems and change his cultural practices to compensate accordingly, if necessary. A grower should consult his insurance agent *before* making any structural modifications and especially before adding any insulation to roof areas.

Modification Technique Air-Inflated External Plastic Covers over Glasshouse

Potential Savings - 40 to 60 percent annual range.

Costs/Square Foot Surface Area Covered - 45 to 65¢ per square foot initial commercially installed cost (labor and material cost each approximately one-half of total cost), replacement every two years at 3¢ per square foot film cost per film layer plus 7 to 10¢ per square foot labor cost for installation.

Possible Action —

Research at the Ohio Agricultural Research and Development Center (OARDC) and other locations indicates that covering the exterior of a glass greenhouse with air-inflated plastic covers (Fig. 4.A.1.) will reduce infiltration and conduction heat losses. To implement, first purchase some six mil plastic film which is ultraviolet light resistant and manufactured especially for greenhouse use.

Fastening devices for plastic are available from most plastic greenhouse manufacturers and suppliers.

Double-layer plastic covers are usually inflated by a 1/30-hp. centrifugal blower with maximum output pressure of 1.0 inch of water column pressure. A "rule of thumb" is to use at least one blower for every 10,000 square feet of greenhouse area. The blower should be mounted before covering is started. Place the inflation fan near the ridge to insure that snow buildup does not close off the air opening.

A damper plate should be made for the air inlet side of the blower, so that the air pressure between the two sheets of plastic can be regulated (Fig. 4.A.2.). The air intake side of the blower should pull outside air to

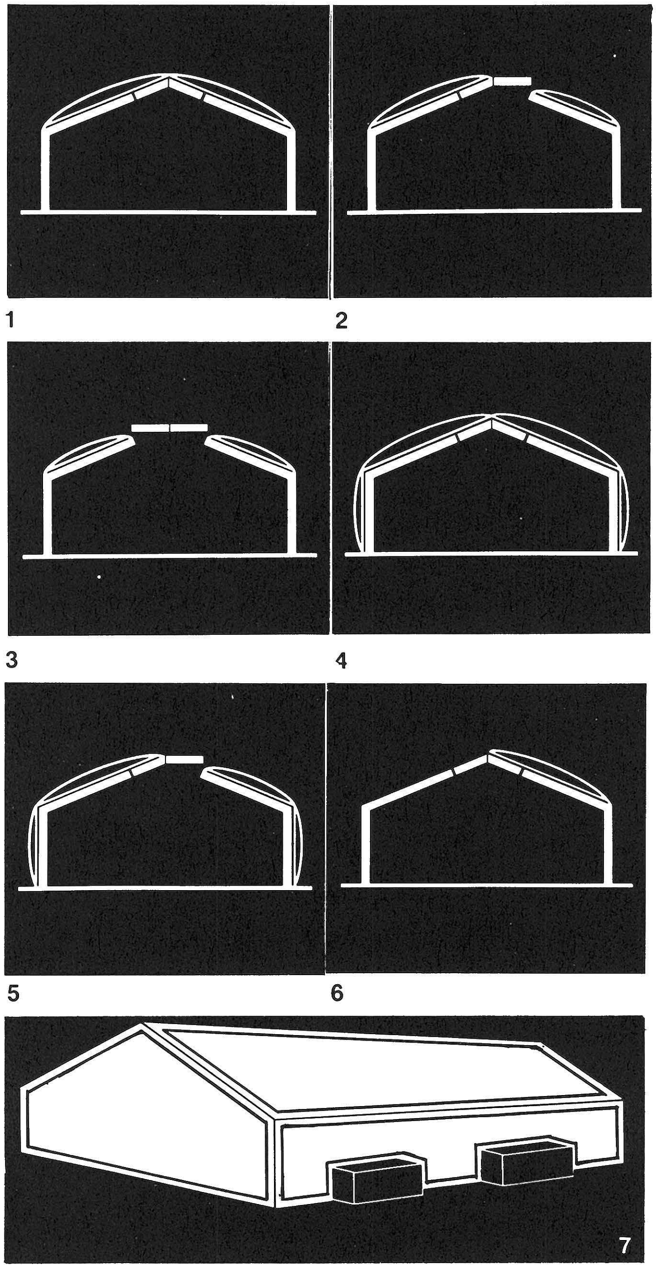


Fig. 4.A.1. Suggested methods of double poly covering:
1. Over the top—eave to eave.
2. Up to the vent.
3. Both vents open.
4. Sill to ridge with one bubble.
5. Sill to vent with one bubble.
6. Separate bubbles on the roofs.
7. Work around vents, fan boxes and doors. You can also cover ends.

Some growers prefer to use separate wall bubbles over side vents of Aspen pad areas which can be removed when warm weather approaches. Monsanto Plastics & Resins Co. photo

4 modification methods

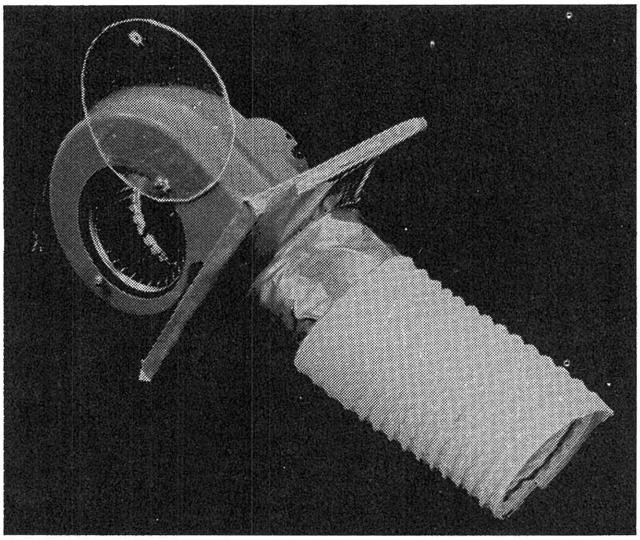


Fig. 4.A.2. Construction of blower damper plate for airflow adjustment.

reduce condensation between the two layers of plastic. Any condensation on the plastic will reduce light transmission.

To further reduce condensation and freeze-up problems, drill a small drain hole in the bottom of the blower housing. Run a sheet metal tube to the blower, placing the blower slightly higher than the inlet opening, so any condensation can drain.

If condensation and freezing are not problems, a four-inch clothes dryer flexible duct tubing and four-inch galvanized stove pipe can be used to connect the blower to the bottom plastic cover. Flexible ducting especially for this purpose is also available from horticultural suppliers.

A pane of glass should be removed from the greenhouse roof and replaced with a piece of 3/8-inch marine plywood or plexiglass panel. The panel is used to hold the inflation duct close to the bottom sheet of plastic. The panel should be fastened to the sash bars and needs to be no more than six to 10 inches wide. A four-inch hole drilled in the panel will hold the galvanized tube near the bottom layer of plastic (Fig. 4.A.3.).

Use a manometer to measure the air pressure between the two layers. This can be made with a three-foot piece of clear plastic tubing (Fig. 4.A.4.) Use enough water to fill a 12-inch section of the tubing. Loop about eight inches of one end up to form a "U." Fasten to the sides of a ruler. This should give two six-inch columns of water. Cut a small hole in the

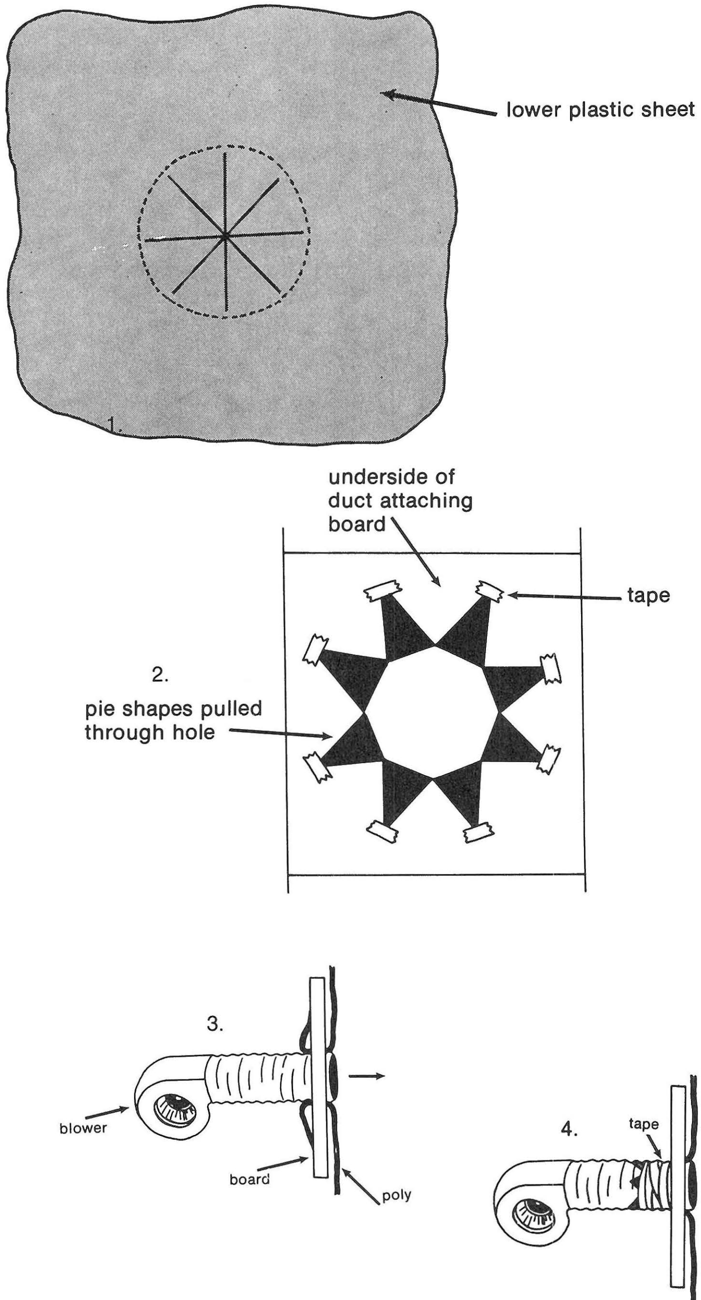
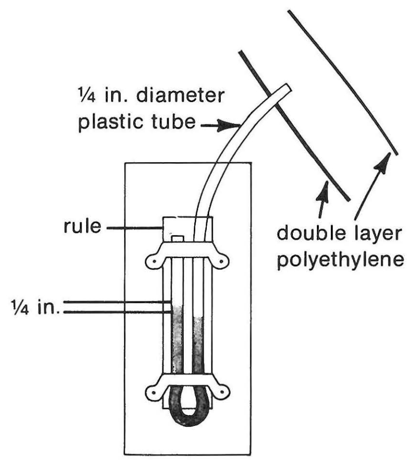


Fig. 4.A.3. Method of attaching duct, panel, and poly.
1. Mark out 4-in. diameter circle in the lower plastic at duct attaching board. Cut into eight pie-shaped segments still attached to circumference.
2. Fold back these segments and temporarily tape to underside of duct attaching board.
3. Insert blower duct through panel and plastic sheet. Release pie shapes from board and tape them to blower duct.
4. Wrap several layers of tape around duct and pie shapes to attach firmly.

4 modification methods



Monsanto Plastics & Resins Co. photo

Fig. 4.A.4. How to construct manometer to measure air pressure.

plastic film some distance from the blower and slide the long leader end of the tube through the hole. The distance between the top of the two columns of water is the water column air pressure between the plastic. Approximately 0.25 inches of water pressure should be maintained when the plastic is inflated. Do not allow pressure to go over 0.4 inch.

Preparing Greenhouse Structure

Step 1. Remove all sharp protruding objects from the outside surface of the greenhouse to prevent puncturing or tearing plastic during application. Cover rough or sharp edges with duct tape.

Step 2. Obtain continuous rail-type fastening devices to achieve uniform and secure fastening of the plastic. BOLT the securing devices to the greenhouse.

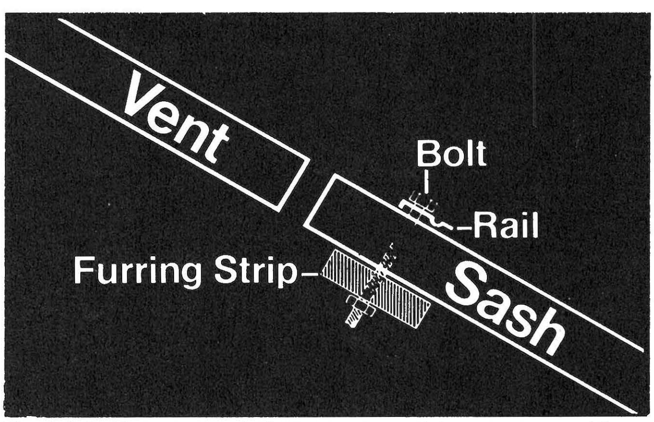


Fig. 4.A.5. To secure poly fasteners to sash bars at areas without cross beams, reinforce with a one-by-three furring strip as shown. Monsanto Plastics & Resins Co. photo

Step 3. Sash bars must be firmly attached to a gutter plate before securing devices are fastened to them. Where weak rafter members are encountered, either repair the sash bars or attach the plastic securing device to the gutter.

Step 4. Attach plastic securing devices to the bottom of the sash bars and just below the vents, if the vents are being used.

Step 5. Wash outside glass with glass cleaning compound or water and brush to insure better light transmission.

Step 6. Horizontal lengths of the rail should be mounted first. Drill one quarter-inch holes through the rail and every sash bar to a structural member to secure the rails firmly to the house structure. The best method is to drill through the rails, sash bars and through the sash beams. If the sash bars rest on steel beams, drill through the sash bar and beam, or bolt the rail with a small steel clamp. If there is no beam under the sash bars where you are mounting the rail, use one-inch-by-three-inch furring strips (See Fig. 4.A.5.).

Bolts and nuts can be inserted into the holes and tightened as you go. You will need a helper on the scaffold or ladder inside the house to help fasten the nuts.

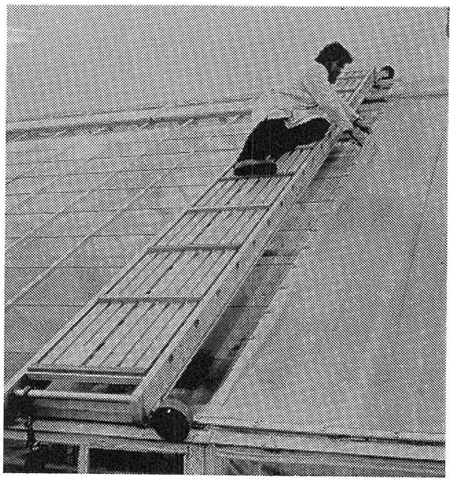
Vertical rails are applied by bolting through a structural member.

Step 7. The use of a single bubble on glass greenhouses should be limited to no more than 110 feet in length and not more than 20 feet in width. Many greenhouses are slightly longer than 100 feet and will require a 110 foot roll. Generally the smaller bubbles are easier to install and control during and after inflation. Smaller bubbles also reduce flapping during high winds.

Houses of greater width and length than in the above guidelines may require more than one bubble. Multiple bubbles may be easily installed with the use of double rail fasteners. Used vertically or horizontally, double rails save mounting time and are less expensive than two single rails. Double rails should be mounted in the same manner as single ones. That is, drill through a structural member whenever possible and secure the rail with one quarter-inch bolts and nuts.

Installation

Step 1. Winds should be at a minimum when the plastic is installed on the greenhouse.



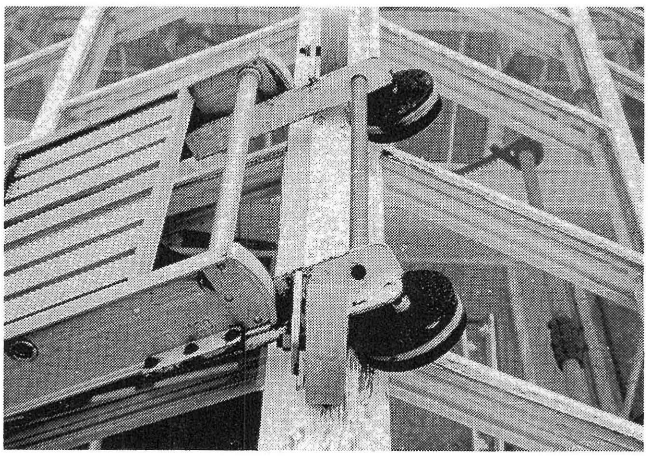


Fig. 4.A.6 Method of construction and operation of a portable scaffold.
The mobile scaffold (above) was made by modifying an ordinary aluminum ladder.
Closeup of roller arrangement at the top of the mobile scaffold (below).

Step 2. After securing the plastic fastening devices to the rafters and installing the blower attachments, the plastic is rolled out over the greenhouse superstructure. A portable scaffold (Fig. 4.A.6.) can be very helpful during this process.

Step 3. The plastic film should be pulled but not stretched to lay freely over the structure.

Step 4. The plastic film can then be fastened with the securing devices. Excessive pulling and stretching of the plastic before or during securing should be avoided because all wrinkles will disappear after inflation. There is also less tearing stress and stretching at the fastener if a loose sheet of plastic is inflated.

Step 5. Once both sheets of plastic are secured, the blower air duct can be attached to the bottom layer of plastic. Carefully make a circle on the bottom sheet of plastic through the four-inch hole in the blower panel. Cut this circular area into eight pie-shaped segments that are still attached at the circumference (Fig. 4.A.3.). Small tape loops on the thumb and forefinger are helpful to hold the bottom sheet away from the top sheet for the initial cut. Working around and above the panel, temporarily fold back these segments and tape them to the under side of the duct attaching board. Insert the fan duct through the panel and just through the new hole in the lower sheet. Release the tape holding the pie-shaped segments and form them around the fan duct. Tape the pie-shaped segments securely to the fan duct with two or three loops of tape. Pull the duct down through the panel until the tape, plastic, and duct make a snug fit with the panel hole. Once this has been accomplished, the plastic film is ready to be inflated.

Step 6. Straps or tie-downs across the top of the plastic sheets are not recommended, as they are more likely to tear the plastic than to hold it in place.

Step 7. Sections of plastic that are not attached directly to a blower can be connected to inflated sections by making small slits and inserting short lengths of air duct. These should be placed near the ridge to avoid being closed off by snow buildup.

Operation and Maintenance

Step 1. Begin inflation as soon as a section of plastic film is secured around the edges. It will take more than an hour to inflate large sections.

Fig. 4.A.7. Typical maximum bubble height will be from 16 inches to 24 inches. Monsanto Plastics & Resins, Co.

Step 2. Cut a small hole in the bottom sheet of plastic to insert the manometer tube. This hole can be closed later with tape. The recommended operation pressure is 0.25-0.35 inch water pressure. The recommended blower will not normally produce more than 1.0 inch water pressure. Do not become alarmed at excessive billowing or separation of the plastic as long as the pressure is less than 0.4 inch water pressure (Fig. 4.A.7).

Step 3. If the pressure is above 0.4 inch of water pressure, the damper on the blower should be closed slightly. If the high pressure persists, cut a small hole in one of the sheets some distance from the blower.

Step 4. Maintain a supply of tape to repair any holes or tears that may occur during or after installation.

The plastic should remain pressurized at all times. Normal operating pressure will keep the plastic from having wind ripples and make it feel soft to a gentle push. Many growers installing double plastic for the first time become alarmed at billowing after inflation. Considerable billowing is normal and effectively allows the outer cover to adjust to variable wind and internal pressure loadings. If allowed to remain deflated for a number of days, the wind-whipped plastic may tear near the fasteners.

Caution

1. Be sure to bolt all cover fastening devices securely and maintain recommended air pressure.

2. Do not place the outside blower air inlet where it can be blocked by snow drifts. Place air inlets to the plastic sheets near ridge to avoid closure under heavy snows.

3. It may be necessary to make special provisions to provide combustion air to unit heaters, if this modification greatly reduces infiltration. See the section on unit heater maintenance.

4. No engineering analyses of the structural responses for this modification have been performed. To date, no serious failures have occurred as a result of double plastic over glass greenhouses located in heavy snowfall areas. Large snow loads do deflate the cover and speed up the melting process. Contact your insurance company before proceeding.

5. Covering with plastic will change the greenhouse environment by reducing light levels by approximately 18 percent and increasing relative humidities. However, night temperatures will be controlled more accurately. It is generally advisable to cover a small portion of your greenhouse first to evaluate these effects on your crop under your cultural conditions before completely modifying your greenhouse.

Modification Technique Thermal Blankets, Thermal Curtains, Heat Sheets

Potential Savings — 20 to 60 percent annual range

Cost — 1 to 12¢ per square foot for curtain materials plus 15 to 30¢ per square foot for sewing.
50¢ to $2. per greenhouse floor square foot installed system cost

Possible Action —

Research at Pennsylvania State and Rutgers State Universities and European research institutes has shown that the addition of thermal blankets to the greenhouse interior decreases heat losses resulting from radiation, convection, and infiltration. Thermal blankets reduce air stratification and the amount of space to be heated. For this reason, they are more effective in a large span house and pulled from gutter to gutter rather than gutter to ridge. Curtains are also more effective in double-layer plastic-roofed greenhouses because they prevent radiation exchange that would normally occur through plastic. Installation of curtains is easiest in clear-span houses.

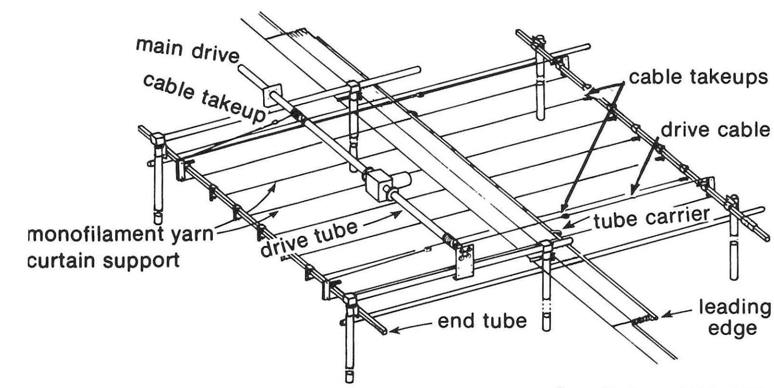
To be effective, blankets must be sealed tightly at the edges. Any openings allow formation of drafts that draw warm air just as does a damper left open in a fireplace. A well-sealed blanket can reduce infiltration effects by enclosing the plants in a tight "box."

The following notes should help you build or buy a system: First, make sure the greenhouse structure is capable of withstanding additional weights and forces, especially with cable supported systems.

Drive

Pulley and cable systems are common drive systems (Fig. 4.B.1.). Make sure a slip clutch is located at least on the main drive to protect the drive mechanism and curtain. Some systems also have slip clutch arrangements at the curtain pulling edge. Each individual cable should have a take-up with it to maintain proper tension. Linear induction motors, which avoid cable and pulley arrangements and pull themselves along on an aluminum track, are also commercially available. If you live near coastal areas, many of the necessary mechanical components for cable drives are available from marine suppliers.

4 modification methods



Cravo Equipment Ltd. photo

Fig. 4.B.1. Cable-supported curtain system.

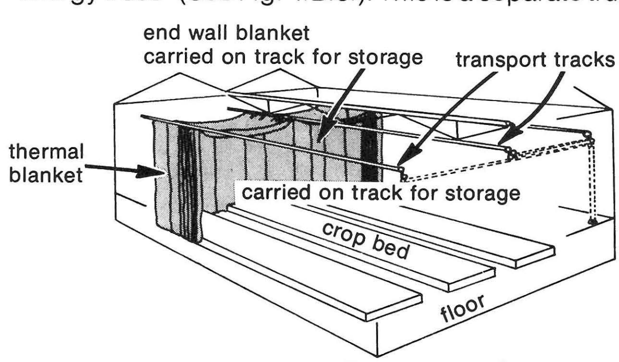
Support System

Curtains may be pulled gutter to gutter, gutter to ridge (not preferable), or truss to truss. In quonset-type greenhouses, pull from greenhouse end to end.

Supports consist of track (similar to the barn-door track) or cables, wires, or rope. For long spans, track is preferable, as it distributes the load onto the greenhouse structure better (Fig. 4.B.2.). Support track with hangers at proper intervals based on the track manufacturer's recommendations and the weight to be supported. Tracks must be aligned parallel to minimize roller binding and curtain damage.

If cables are used to support the curtain, hang the curtain from small pulleys rather than drag it over the cables. This reduces wear on the curtain, lessens the amount of force necessary to move the curtain, and assures that the curtain will retract when the leading edge is pulled back. Each supporting cable should have a takeup with it to maintain proper tension (See Fig. 4.B.1.).

During new construction it is wise to install an "energy truss" (See Fig. 4.B.3.). This is a separate truss



Pennsylvania State University photo

Fig. 4.B.2. A track-type thermal blanket. Note side and end curtains.

(cord) that goes below the gutter-to-gutter cord by about 16 inches. The truss allows the support of heat pipes and trellis systems below the blanket and provides a clear span for the blanket. With this arrangement, some heat pipes should be installed right beneath the gutter to melt snow quickly during heavy snowfalls.

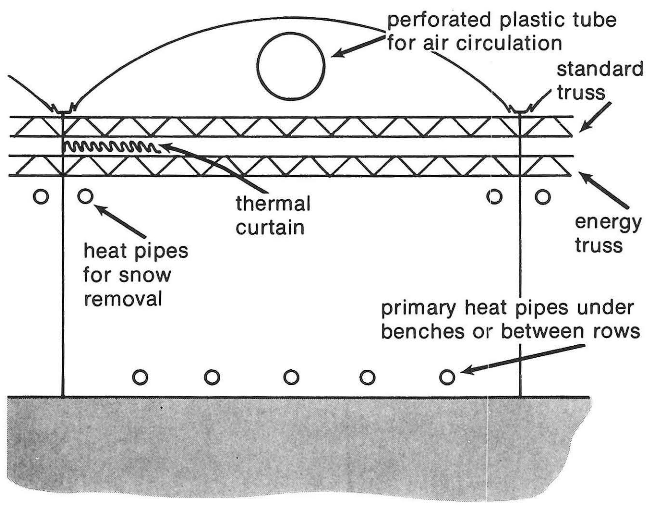


Fig. 4.B.3. Possible layout of an energy truss greenhouse.

Blankets

1. A blanket with a reflective surface will reduce heat use annually by 10 to 15 percent more than a clear blanket. Properly designed blanket systems can reduce radiant heat loss by any of the following ways (Fig. 4.B.4.):

   a. Reflecting radiant energy back to the crop.

   b. Not absorbing radiation and not reradiating (emitting) the absorbed energy to objects beyond the blanket,

   c. Being opaque to thermal or long wave radiation, so that objects beneath the blanket cannot "see" objects beyond the blanket (a condition necessary for radiant heat transfer.)

It would seem logical to install reflectorized curtains with the reflectorized surface facing in to reflect all radiation back to the crop. However, there are other factors to consider. Reflectors are not good absorbers of radiation. If the reflectorized surface faces inward, radiant energy is reflected back to the plants, but the blanket absorbs little energy and stays relatively cool. The cool blanket and high greenhouse humidities cause heavy condensation to form on the blanket and runoff to occur. Additionally, the black exterior surface,

4 modification methods

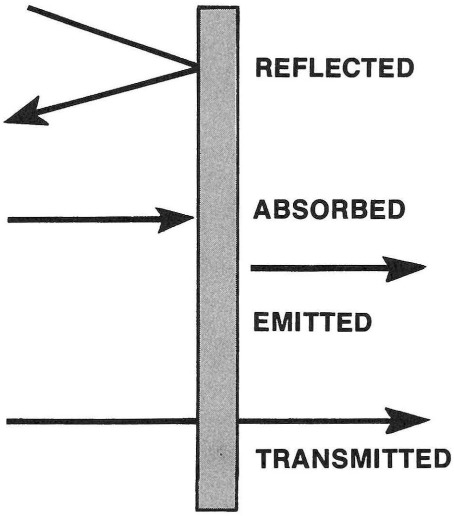


Fig. 4.B.4. Action of thermal blanket.
1. Reflective surfaces reflect radiation back into plants.
2. Low emissivity (highly reflective) surfaces minimize radiation absorption and reradiation to objects beyond the blanket.
3. Opaque materials prevent radiation transmission.

a good radiation emitter, is free to radiate energy beyond the blanket. If the reflectorized surface is facing out, the blanket can absorb energy and stay warmer, condensation and runoff problems are reduced, and radiation is minimized by exposing the lowest emitting surface to the outside. In practice, heat savings differ little whether the reflectorized surface is facing in or out.

Ideally, both surfaces should be reflectorized. However, tests indicate little difference in performance between one or two reflectorized surfaces.

Table 4.B.1 lists radiation properties of selected curtain materials. Remember that emissivity values vary from zero to one and that values close to one indicate good absorbers and emitters. Values close to zero indicate poor absorbers (good reflectors) and poor emitters. (See radiation in heat transfer section for further discussion).

2. A solid blanket will reduce annual heat use 10 to 30 percent more than a porous blanket. Porous blankets not only allow some passage of air but allow passage of water vapor also. Water vapor reaching the cold roof may condense and drip back onto the crop. When condensation occurs, energy carried by the water vapor is released to the cold glass surface where it is conducted outside through the glass and lost. To stop air movement effectively, blanket materials must be tightly woven.

3. A multi-layer or thick curtain will reduce heat flow more than a thin curtain because of the reduction in conductive heat loss by the blanket material. Heat conduction across any blanket is reduced by thin layers of insulative, still air on either side of the blanket. "R" values for different blanket materials are listed in Table 1.B.1. of the heat loss calculation chapter.

4. Heat retention differs little between properly installed aluminized curtains. Therefore, the more important blanket characteristics are ease of fabrication and handling, tear strength, weatherability, longevity, flammability, and cost.

5. Fabric choice also depends on the drive system chosen. The linear induction motor system does not

TABLE 4.B.1. Radiation properties of selected curtain materials*.**

Material	Manufacturer	Measured Transmittance	Calculated Emittance	Calculated Reflectance
	Single Layer			
Foylon 2001-P, aluminum side	Duracote	0	0.30	0.70
Foylon 2001-P, fabric side	Duracote	0	0.45	0.55
Black polyethylene 6-mil	Monsanto	0.15	0.40	0.45
Aluminized mylar		0	0	1.00*
Woven clear polyethylene 10-mil	Loretex	0.45		
Infrane X30	Scasar	0.35	0.45	0.20
Clear polyethylene 4-mil	Monsanto	0.70	0.10 to 0.20**	0.20 to 0.10**
Clear 602 polyethylene 6-mil	Monsanto	0.60		

*Assumed value
**Published value (Walker and Walton, 1969, emit = 0.10 and Walker et al 1972, emit = 0.20)
***Adopted from: Simpkins, Joel C., David R. Mears, and William J. Roberts. "Reducing Heat Losses in Polyethylene Covered Greenhouses," ASAE Paper 75-4022, June 1975.

have the pulling power of a cable and pulley system and needs a lighter material. The cable and pulley system needs a stronger material because higher forces stress the blanket and seams, especially if the blanket is dragged on the wires.

6. Fabric life depends mainly on the reaction with ultraviolet light (UV) and the kind of structure in which it is installed. Glass stops UV light and prolongs the life of UV-sensitive curtains. Polyethylene houses are more transparent to UV light and provide less protection for UV-sensitive curtains.

7. If polyethylene curtain material is used, provide at least a three-inch air gap between the curtain and any heating pipe.

The most expensive parts of a thermal blanket system are the mechanical system (especially if powered), blanket sewing and grommet insertion, and labor costs for installation. The blanket material is probably the least expensive part.

Material life must be studied when considering curtain cost. For example, two materials may have the same cost per square foot per year, but one may last twice as long. The shorter life material will have the extra expense of an additional curtain construction and installation.

Controls

Curtains may be opened and closed automatically with a photocell or time clock. Special controls may be needed to automatically open the curtain slowly in the morning to prevent cold shock to the plants (see discussion of thermal blanket problems). Use a snow warning device (commercially available) to open curtains automatically, and if necessary, turn on additional heat pipes beneath gutters during snow storms. Provide an automatic emergency backup power source or provisions to open the curtain manually in case of power failure. Provide a fail-safe alarm system for manual backup methods. Use quality components, follow wiring codes, and protect components from physical damage and environment.

Shading

The blanket system is more economical if another use can be found for it. Black curtains can also be used for day-length control for some photoperiodic crops. Tight fits at mating surfaces are necessary for effective light control. Semi-transparent materials can be used for shading on sunny days depending on the degree of shading desired. Reducing the amount of sunlight reaching the plants cuts down the ventilation requirement and minimizes electricity use for fan ventilation systems.

There is no blanket material that provides ideal heat retention and shading performance. White poly, clear poly with white dots, and light gray plastic have been used with some success. UV-sensitive materials should be used only in glasshouses. White poly should last three to five years beneath glass. Porous shading fabrics now available may be used for thermal blanket application with some sacrifice in heat retention.

Problems

Problems associated with thermal blankets are:

1. They are more difficult and expensive to retrofit into some structures because of structural support posts, trellis support systems for some crops, and the relocation of heat and water pipes and lights placed above the gutter to gutter line. Lowering unit heaters may cause safety problems.

2. Daytime storage of curtains may cause heavy spot shading with a corresponding crop yield reduction. Ideally, the effects of such shading can be minimized by placing retracted blankets on the north side of the house or gutters or over pathways and exposing the curtain reflective surface.

3. A good curtain system is an effective insulator, so heavy snow loading on the greenhouse roof may be a problem. This is usually handled in one of three ways:

a. If snow is anticipated, the curtains are left open when greenhouse personnel go home at night. To be safe, the blanket frequently has to be left open if there is the slightest chance of snow.

b. Personnel living close to the greenhouse or a night/weekend watchman are responsible for opening the curtain if snow falls.

c. Snow detectors can be mounted on the greenhouse roof to open the curtain automatically in case of snow. This probably is the safest arrangement and saves the most energy.

4. Non-porous curtains collect condensation dripping off the roof. The weight of the collected water can damage the curtain and cable supports. Punching small holes at trouble locations may reduce this threat but cause problems for plants underneath.

5. Because infiltration is greatly reduced, humidity beneath the curtain increases. Some people have re-

ported an increase and some a decrease in related disease. More research is under way, but it appears that leaf temperatures (higher under the curtain due to less radiant heat loss) and type of crop play a part and that for some crops, disease is actually less.

Under extremely cold conditions, frost or ice can build up inside the glass and substantially reduce morning light. The heavy ice meltoff also causes undesirable dripping.

6. Care must be used when the curtain is initially opened in the morning. Cold air falling through the open curtain can injure the plants. This can be reduced by changing to greenhouse day temperature one-half hour before curtain opening and/or retracting the curtains slowly to allow mixing of the air.

7. The system can become a mechanical nightmare with lots of little adjustments and things to go wrong.

With the exception of some retrofitting, most of these problems seem solvable, and research is continuing. Some retrofitting in older houses is not economical because of numerous posts and the expense of relocating lights, water pipes, and heating units or pipes. The physical layout of the greenhouse may make such relocations impractical or undesirable.

Air Blanket

An air-inflated blanket system is also commercially available. The transparent blanket is mounted on the inside of the roof (preferably from gutter to ridge to allow condensate runoff) and normally kept inflated. During periods of snowfall this blanket may be deflated to allow passage of warm air to the roof. The system may also be used on side and end walls. Life expectancy is about two years, and there is a reduction in light. Fuel savings anticipated by the manufacturer total approximately 40 percent with the complete roof covered. As with other blanket systems, to be effective the air blanket must form a tight seal at laps and splices. Installed cost for 30,000 square feet of air blanket is estimated at 15¢ per square foot of blanket. Material cost is from 7 to 13¢ per square foot depending on quantity.

CAUTION

1. *Do not* use unmovable plastic sheets stretched horizontally from gutter to gutter for a heat barrier. These reduce light at low sun angles by reflection and may insulate too effectively to allow snow melting off the roof and gutter areas.

2. Some curtain materials are flammable. Check with your insurance company before installing a curtain system. Your insurance rates will depend on the flammability of the material, safety devices, and quality of the controls for retracting the curtain.

Modification Technique Applying Sealant to Glass Laps

Potential Savings — five to 40 percent annual range

Cost — 30 to 50¢ per square foot of area covered, installed commercially

Possible Action —

The application of sealant to glass laps will reduce infiltration heat losses in glass greenhouses. The extent of savings depends heavily on the condition of the house and the windiness of the location. Older glass greenhouses with wooden frames and in average or below-average repair usually realize the most savings. It is usually not profitable to seal new glass greenhouses unless done during construction.

A 20 foot x 90 foot (18,900 cubic foot) greenhouse in reasonably good condition with 24 in. x 26 in. glass panes and a 1/32 inch crack at glass laps will have a total infiltration area of over 4.5 square feet. These openings will provide approximately 0.75 to 1.5 air exchanges per hour. At one air change per hour and with an inside-outside temperature difference of 30°F, more than 11,000 Btu per hour will be required to heat the infiltrating air — to inside air temperature.

Sealants are usually applied commercially. Dirt and moisture are first blown from between the glass laps and a clear silicone-based sealant injected with a high pressure propellant (Fig. 4.C.1.). The material readily

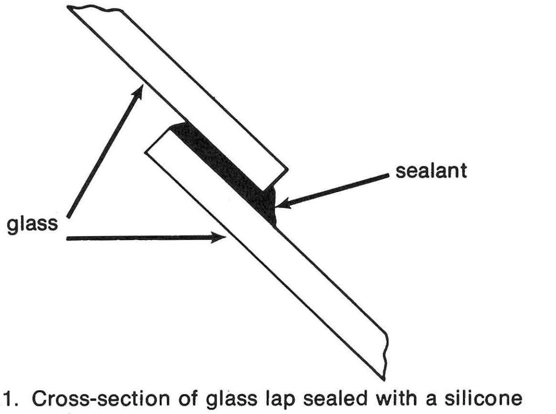


Fig. 4.C.1. Cross-section of glass lap sealed with a silicone sealant.

adheres to clean glass and is non-hardening. Thus it can maintain the lap seal during glass expansion and contraction and prevents glass slippage. This process is permanent because the sealant cannot be easily removed from the lap area. (Some sealants are guaranteed for 10 years). If glass breakage occurs, a special knife may be used to cut the sealant and allow glass removal. Tubes of sealant are available for hand-sealing after glass replacement.

Because the material is clear and only a small portion of the glass is affected, light reduction is negligible. The increased tightness of the house allows more efficient use of supplemental CO_2 and increases humidity levels. The increased humidity is generally desirable for plant growth but may cause heavy condensation, dripping, and plant disease problems unless proper ventilation and air circulation is provided (see ventilation section).

Caution

Provide adequate combustion air for unit heaters. Substantially reducing infiltration may not allow adequate combustion air for unit heaters within the greenhouse. (See the section on unit heater maintenance).

Modification Technique Polystyrene Pellet Insulation

Potential Savings — 60 to 90 percent annually

Cost — 50¢ to $1. per square foot for equipment and material. Four inches of pellets are 20¢ per square foot of greenhouse surface (60¢ per cubic foot). Installation cost unknown.

Possible Action —

Research at the Ohio Agricultural Research and Development Center (OARDC) has shown that over 80 percent of all supplemental greenhouse heating is required at night. Further studies at OARDC and in Japan indicate that a polystyrene pellet nighttime insulation technique could reduce greenhouse nighttime energy requirements by 80 to 90 percent. At the OARDC, four inches of pellets are pumped between the walls of a double-wall greenhouse at sundown and removed at sunrise for an additional insulation "R" value of 16. (R = four for each inch of pellets).

This system is used on a small scale in commercial Japanese glass greenhouses where snow is not a problem. The Japanese form a double wall by installing plastic sheeting material approximately three inches behind the glass.

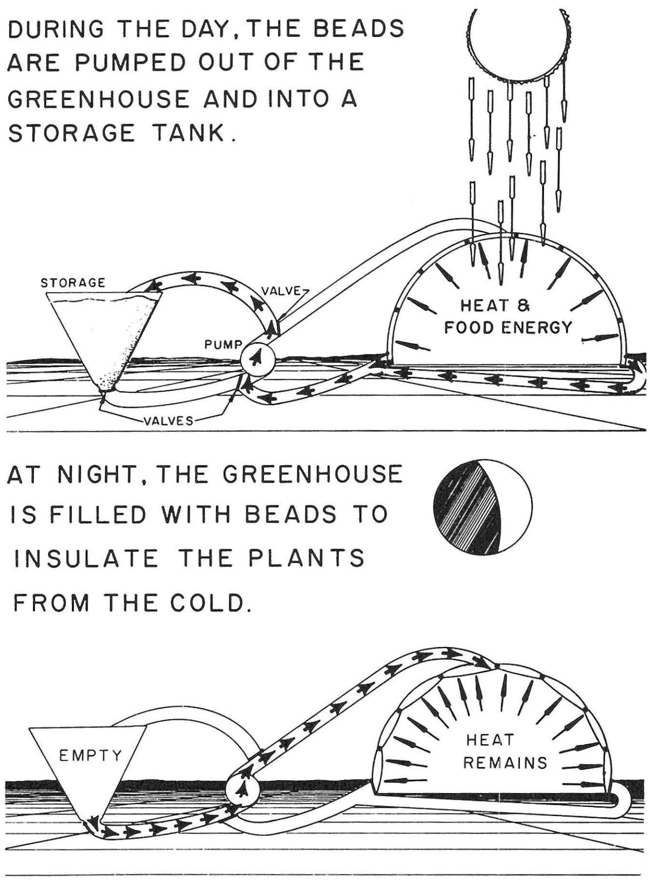


Fig. 4.D.1. Operation of a polystyrene pellet insulation. greenhouse.
During the day, the pellets are pumped out of the greenhouse and into a storage tank.
At night, the greenhouse is filed with pellets to insulate the plants from the cold.

In most cold climates, and especially with gutter-connected houses, snow accumulations are a problem with well-insulated greenhouses. Accumulation of snow can damage or break brittle materials such as glass and interfere with light transmission during the day. Because snow load forces are better distributed over the supporting framework of air-inflated double plastic covers than with glass, the OARDC approach is to use conventional double-plastic covers that are air inflated during the day and filled with pellets during the night (Fig. 4.D.1.)

As more research needs to be done, the OARDC cannot make a general recommendation that growers construct pellet transport systems for insulating their greenhouses. Instead, the following information is meant to inform growers of the current findings for the OARDC experimental system.

4 modification methods

Polystyrene pellets with a minimum diameter of one-eighth-inch and treated with a fire retardant are preferred. Pellets are pumped directly through blowers with an air/pellet ratio of 25:1 during filling and 50:1 during emptying the greenhouse cover. The one-horsepower blower used is rated at 1,000 CFM while operating at 3,450 RPM and one-inch static water pressure. It will pump about 45 cubic feet of pellets per minute at maximum capacity. The mixture of air and pellets is pumped into the plastic layers at pressures less than one-inch water pressure to prevent rupturing the plastic. This is accomplished by evacuating air from between the plastic sheets with a similar-sized blower while filling. This evacuation procedure also controls the thickness of fill and maintains film tension on the insulated system at night.

Static electric cling of the pellets to the plastic and each other can be a serious problem unless controlled by such chemicals as glycerine. Adding one gallon of glycerine to each 1,000 cubic feet of pellets prevents static problems for many months. Other antistatic chemicals recommended for garments have also been effective. The precise life of the antistatic agents is unknown.

Moisture in the pellets and between the plastic is a serious problem during sub-freezing weather. A thin layer of pellets can freeze on the inside surface of the outside cover. Likewise, moisture in the pellets can reduce the insulation effect. Therefore, all blowers or air inlets to blowers are ducted to outside the humid greenhouse, and the pellet storage is periodically air dried with one of the blowers on dry sunny days.

Pellets are stored outside the greenhouse growing area because the growing area is valuable space, and the inside air is too humid. Storage should be in a dark, dry location because sunlight can slowly deteriorate the polystyrene. Large plastic bags may be used to store the pellets, as the pellets weigh only one pound per cubic feet. The life of the pellets is unknown, but no apparent deterioration has been evident after numerous cycles through the transport blowers.

Many refinements are still required in the present system to reduce maintenance and operating costs and to control moisture. Research on improving pellet transport, distribution, and storage systems is continuing.

An alternative use of a pellet system may be photoperiod control. Although pellets are generally opaque, it is difficult to get a 100 percent blackout. The last section to fill is the most difficult. Temporary shading may also be possible through moisture and static cling. Both techniques tend to leave a thin layer of pellets on the plastic surface. Shading by partial filling (or emptying) is difficult to do uniformly.

Modification Technique Liquid Foam Insulation

Potential Savings — 40 to 75 percent (estimated)

Cost — 30 to 50¢ per square foot for equipment and materials. Installation cost unknown.

Possible Action —

Research at universities in Arizona and New Hampshire has shown that nighttime greenhouse heat requirements can be reduced using liquid foam between the double-plastic layers. The foam is assumed to act as a partial radiation and air convection barrier.

A major advantage of a foaming system is the approximate 1:200 volume ratio from liquid to foam. The foam can be stored as a liquid during the day in a relatively small tank and expanded 200 times after sundown. The foam is continuously generated during the night to make up for that which reverts to liquid. Liquid is returned by gravity to the storage tank in a special gutter system between the plastic sheets along the base of the rafters.

A major problem still under study in New Hampshire is that sub-freezing temperatures break down most foams. It is believed that some liquid foam products will stay expanded at temperatures below freezing, but these products have not been thoroughly tested.

An important consideration with foam may be its alternative use as a shading material, but no test data is yet available on the percentage of light reduction. The foam will probably not work for photoperiod control because it is somewhat transparent, depending on bubble size.

Modification Technique Sidewall Insulation

Potential Savings — Depends on surface area and condition. Insulating north wall only, up to 10 percent. Insulating other sidewalls, also up to 10 percent.

Costs — $1 per square foot (including installation) to replace north wall with insulated wall.

$0.05-0.06 per sq. ft. for laminated air bubble films.
$1.25-2.50 per sq. ft. for rigid twin wall plastic.
$0.25-0.30 per sq. ft. for extruded polystyrene board (1 in.).
$0.06-0.07 per sq. ft. for Microfoam™ (¼ in.).
$0.06-0.08 per sq. ft. for air-separated polyethylene.
Material costs per sq. ft. covered unless otherwise indicated.

Possible Action –

The two basic classes of sidewall insulation are transparent and opaque. Opaque insulations are frequently used on north walls or along sidewalls up to plant height. Both kinds of insulation must be either waterproof or protected from water. Sidewall insulation reduces conduction and infiltration losses. Opaque or reflective insulations also minimize radiant heat losses. Both types slightly reduce light levels in the greenhouse.

North Wall

The greenhouse north wall may be insulated by covering the existing walls with insulation or by completely replacing the north wall. Studies in Connecticut have shown that the north wall can be replaced for less than $1. per square foot including installation. Fuel savings depend on the amount of north wall area in comparison to the total external surface area. Annual fuel savings up to 10 percent are possible.

Opaque Insulations

Walls not facing north can be covered with opaque material up to plant height. Materials commonly used are listed; all have high "R" values for relatively small thickness: (See "R" values listed in Table 1.B.1.).

1. Polystyrene beadboard: unless protected by a vapor barrier will absorb moisture and lose insulation value. Protection of exposed surfaces is also necessary to prevent deterioration by sunlight and to minimize combustion hazard from polystyrene, which is combustible.
2. Extruded polystyrene boards (Styrofoam™): acts as a vapor barrier but is also combustible. Protection of exposed surfaces is necessary to prevent deterioration by sunlight. Styrofoam™ is chemically inert, will not support plant or animal life, and is resistant to ground, chemicals, and microorganisms.
3. Polyurethane board: is a vapor barrier. However, when in contact with water, it should have a protective coating to prevent degradation. Polyurethane is combustible, and if burned, emits fumes toxic to humans.
4. Foam packing material (Microfoam™): is its own vapor barrier and will not support fungus growth. Microfoam™ is combustible and will also deteriorate on exposure to sunlight unless protected.

To reduce the fire hazard for these insulation boards, cover with a 29-gauge galvanized steel, 0.032-inch aluminum, or flame-retardant coatings.

Do not use foamed-in-place insulations inside the greenhouse, as on curing they give off fumes toxic to plants. Of these foams, urethane and polystyrene are highly flammable, and ureaformaldehyde will degrade in sunlight.

Glass fiber insulation is not recommended for greenhouse applications. Because of the high humidities, it is difficult to construct vapor barriers correctly to prevent moisture absorption. Wet glass fiber has little insulation value and is very difficult to dry out.

Transparent Non-rigid Wall Insulations

Aircap™ is constructed with two layers of plastic laminated to trap air bubbles. It is advertised as reducing heat flow through walls by up to 35 percent and having a light transmission of approximately 12 percent less than window glass. Aircap™ may be stapled to wooden sash bars or fastened to aluminum frame with double-sided tape.

Plastic films may be fastened with wood lath or double-sided tape to provide some insulation and reduce infiltration effects.

Inflated layers of double plastic are also popular and decrease conduction as well as infiltration heat losses. Mounting procedures are similar to roof mounting procedures. (See air-inflated external plastic cover section.) Sometimes continuous sheets are run from the greenhouse ridge to the foundation as part of the roof covering.

Transparent Rigid Wall Insulations

1. Double Wall Glass Including Thermopane™
Some growers have placed glass on the inside of wall sash bars to add insulation. Sometimes special "double-cut" sash bars are installed to simplify this. The "R" value of Thermopane™ glass is approximately 1.5. Regular Thermopane™ glass as supplied by glass distributors is usually not economical.

2. Double Wall Fiberglass

Fiberglass walls may be insulated by adding a second sheet to provide an air space. Special spacer inserts are available from fiberglass suppliers to match corrugated fiberglass and simplify construction. Insulation value is similar to double glass and is less expensive, but light transmission is not as good.

3. Double Wall Plastics

Acrylite S.D.P.™ is made in North America by CY/RO Industries. It is manufactured in rigid sheets about four feet wide in standard lengths of eight, 10, 12, 14 and 16 feet and can be custom-made to longer lengths. The acrylic material consists of two layers separated about ½-inch with ribs about every ½ inch. It diffuses and transmits 83 percent of the light compared to glass at 89 to 90 percent, but the total amount of light reaching the plants is about the same as roof bars can be spaced every four feet instead of every two. Fewer heat pipes are needed because of the insulation factor (R=1.72). Life is unknown, but other acrylics last more than 20 years under similar conditions. The material has excellent mechanical strength, and installed on commercial ranges, has withstood severe hailstorms. The insulation value of the material helps to keep the inside surface warmer, somewhat lessening condensation problems. If installed at an angle of 25° (app. 1:2) or greater, condensation will run off and can be collected. The material is somewhat permeable to water vapor and must be installed with ribs running vertically and drainage provided at the bottom mounting.

Tuffak - Twinwal™ (R=1.61) is manufactured by Rohm and Haas Company in rigid sheets four feet and 80 cm wide. Standard length is eight feet with custom lengths available. The polycarbonate material consists of two layers separated by about one-fourth inch with ribs every one-fourth inch. The maximum panel sizes for no load conditions should be no greater than four by four feet and two by eight feet. For a 20 lb/square foot design load as recommended for greenhouse roofs, the maximum span is 2.5 x 4 feet, with ribs running across the short dimension. Total light transmittance is 77 percent, similar to double-pane glass glazing, and transmitted light is diffused by the material. Polycarbonate materials tend to yellow after prolonged exposure to ultraviolet light and reduce light transmission somewhat. Life is unknown, but probably will equal six to 10 years.

Replacing single pane glass with either of these last two materials will reduce conduction heat flow by approximately 40 to 50 percent. Some of the disadvantages include:

1. High cost, \$5. to \$7. per square foot installed,
2. Needs special mounting to allow for the high thermal expansion of these materials,
3. Possible reactions with pesticides or other chemicals might accelerate deterioration.
4. Flammability similar to plexiglass.

Caution

1. Some of these materials are combustible and may constitute a fire hazard if improperly used or installed. Protect them from fire and install as directed by the manufacturer. If your greenhouse is covered by building codes, check them for compliance. Some codes restrict the use of certain materials. Consult with your insurance agent.
2. *Do not* apply these materials to the greenhouse roof area unless the greenhouse frame has been properly reinforced or sufficient heat is available to melt excessive snow quickly. Excessive insulation will retard the melting of snow and may cause structural damage from overloading. Also check with your insurance agent.
3. With light-sensitive crops, it may be advisable to insulate a small portion of your greenhouse to test the effect on your crop under your cultural conditions *before* modifying your whole greenhouse.
4. Substantially reducing air infiltration may not allow adequate combustion air for unit heaters in the greenhouse. (See the section on unit heater maintenance.)

Modification Technique Insulating Foundation Walls

Potential Savings — 3 to 6 percent annually

Costs/Square Foot Area Covered — Polystyrene boards 25 to 30¢ per square foot material cost (1 inch), Microfoam™ 6 to 7¢ per square foot material cost (one-fourth inch).

Possible Action —

A typical uninsulated six-inch poured concrete greenhouse foundation wall has an "R" value of 1.33. The addition of one inch of polystyrene (R=4.0) to the wall increases the wall "R" value to 5.33 for a heat flow reduction of 67 percent.

Insulation is best added to the outside of the foundation wall. This procedure will:

1. Reduce stress and subsequent cracking of the concrete because of outside air temperature cycles.
2. Add to the thermal mass of the building for daytime storage of solar heat and reduce greenhouse air temperature fluctuations.
3. Prevent installation problems with perimeter wall heat pipes.
4. Allow safer use of flammable materials.

Any insulation material used, whether inside or outside, should be waterproof. Most materials can be glued directly onto the concrete, if the concrete is first cleaned. Reflective materials should be placed inside the greenhouse between heating pipes and the wall. Do not allow the reflective surface to touch the heat pipes.

Rigid extruded polystyrene (Styrofoam™) and polyurethane boards are frequently used. Bury them at least 18 inches deep along the wall and cover their surface with one-eighth inch cement asbestos board to protect them from physical damage and weathering. Some spray-on insulations may also be considered if applied on the greenhouse outside. (See opaque insulations in previous sidewall insulation section.)

Caution

1. Some of these insulation materials are combustible and may constitute a fire hazard if improperly used or installed. Protect them from fire and install as directed by the manufacturer. If your greenhouse is covered by building codes, check them for compliance. Some codes restrict the use of some materials. Check with your insurance agent.
2. Fumes from spray-on foams may be harmful to plants.

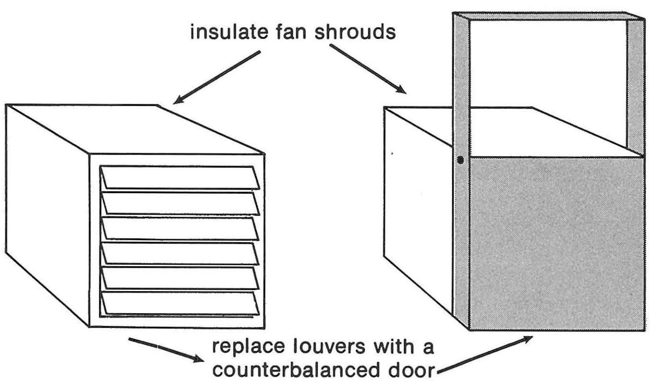


Fig. 4.H.1. Minimizing heat losses from fan shrouds and louvers.

Modification Technique Reduce Heat Losses Through Ventilation Fans

Potential Savings — Up to 5 percent (estimated)

Cost — 25 to 30¢ per square foot for polystyrene boards (one inch) 6 to 7¢ per square foot for Microfoam® sheets (one-fourth inch).

Possible Action —

Exposed metal fan shrouds lose heat by conduction through the exposed metal and allow infiltration through multi-slatted louvers. The metal shrouds may be lined with polystyrene boards, Microfoam™, or Aircap™ to reduce conduction losses. (See discussion on opaque insulations in sidewall insulation section.)

Infiltration losses can be reduced on some fans by replacing the slatted louvers with a counterbalanced door hinged at the top (Fig. 4.H.1.). This greatly cuts down on the number of cracks that can leak air to the greenhouse (see Caution 1).

If a ventilation fan is not needed during the winter, seal the fan opening at the wall with insulation boards or plastic sheets. Make sure the fan cannot be turned on either automatically or manually while it is sealed off.

Caution

1. If fan louvers are replaced with a counterbalanced door, make sure the door is counterbalanced properly to provide minimal resistance to the fan. Excessive back pressure may overheat and damage the fan motor and reduce the capacity of the fans.
2. Some of these insulation materials are combustible and may constitute a fire hazard if improperly used or installed. Protect them from fire and install as directed by the manufacturer. If your greenhouse is covered by building codes, check them for compliance. Some building codes re-

strict the use of some materials. Check with your insurance agent.

Modification Technique Heating System Modifications

Potential Savings — 6 to 20 percent annually (automatic tube cleaners), 8 to 16 percent annually (turbulators)

Cost — Approximately $5,000 per boiler for automatic firetube cleaner. Turbulators vary with size of firetube. Approximately $6.50 per three-inch diameter firetube.

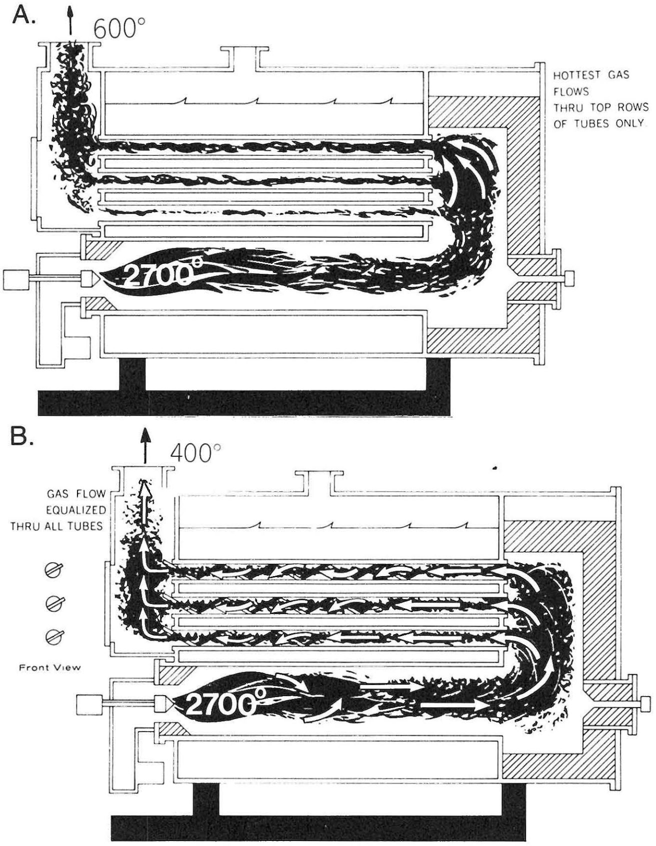
Possible Action —

Automatic Firetube Cleaners

The buildup of soot on the inside of boiler firetubes acts as insulation and reduces heat transfer between the hot gases and firetube. (See section on boiler maintenance.) Automatic tube cleaners are available that use periodic puffs of compressed air to remove soot from the firetubes. The air puffs are directed against the draft, causing the soot to burn in suspension instead of being discharged up the stack. Every tube is automatically cleaned at least once an hour, but the compressed air requirement is kept low by cleaning only a few of the tubes at one time. Aside from eliminating manual labor costs, a 6 to 20 percent decrease in fuel consumption is claimed. The cleaner is suited to all types of firetube boilers including two, three and four pass, heavy oil, coal, and wood-fired but is most economical with very dirty fuels.

Turbulators

Normally, hot gases flow smoothly through a boiler firetube and leave a thin layer of "still" gases along the tube walls. By causing more air turbulence in the firetube, more air is brought into contact with the firetube, and heat transfer is increased (Fig. 4.I.1.). Turbulence can be created by contoured metal strips (turbulators) that can be inserted into the firetubes of gas, oil, or combination gas/oil firetube boilers. Greenhouse growers in northern California who have installed them claim an eight to 16 percent savings on annual fuel bills.



Photo, Fuel Efficiency; Inc., Newark, N.Y.

Fig. 4.H.1. Boiler before (A) and after (B) insertion of turbulators

Stack Heat Recovery Units

Heat not transferred from the hot gases to the firetube is normally discharged out the stack. However, this heat is not all wasted, as some heat is necessary to carry the products of combustion up the stack. The installation of stack-heat recovery units can allow recovery of some of the heat normally lost out the stack.

Gas-to-liquid heat recovery devices can be used to supply hot water to soil heating pipes or to heat process water from boiler flue gases. Dutch growers commonly use gas-to-water stack heat recovery devices on natural gas boilers for soil heating and use the cooled flue gas for CO_2 enrichment.

The most effective applications for this device occur when the flue gas temperatures from the boiler exceed 500°F. However, in some cases these devices may be economically applied to flue gas temperatures of less than 500°F.

5 miscellaneous methods

Miscellaneous Methods

A few methods of energy management do not fit the other categories but are equally important. Some of these methods are best applied to new site selection or to new construction, important considerations for the grower who is expanding his operation.

Method — Windbreak To Cut Wind Force

Potential Savings — 5 to 10 percent annually, but under severe conditions, up to 51 percent annually has been documented.

Cost — Variable, depends on size and extent of windbreak

Possible Action —

Wind acts to remove the thin layer of insulative still air next to the greenhouse outside surface. Also, increased wind velocity increases the rate of natural air exchange (infiltration) through leaks in the structure. In comparison to still air, a 15 mph wind can double heat losses (Fig. 5.A.1.). Wind damage to the greenhouse structure can result from glass breakage, plastic fatigue, and dust erosion.

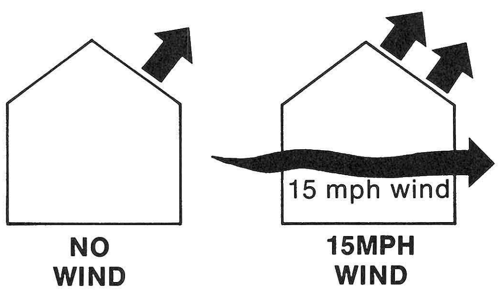


Fig. 5.A.1. A 15-mph wind can double greenhouse heat loss.

Any obstruction that breaks the force of the wind, such as a wall, fence, building, or hill, is a windbreak. As wind strikes an obstruction, it moves over and around it. The extent of downwind protection is related to the height, length and porosity of the windbreak. A solid barrier is not as effective as a porous barrier because the solid barrier creates a strong vacuum on the downwind side. This creates turbulent downdrafts behind the barrier. A porous barrier reduces the vacuum and improves the windbreak's effectiveness (Fig. 5.A.2.) Research has shown that a windbreak porosity of 50 to 60 percent is best.

Windbreaks should be situated between the prevailing winter winds and the structure to be protected. U.S. Weather Service statistics indicate that prevailing wind conditions in Ohio for the month of January are roughly equal in direction from NW, SW, to SE.

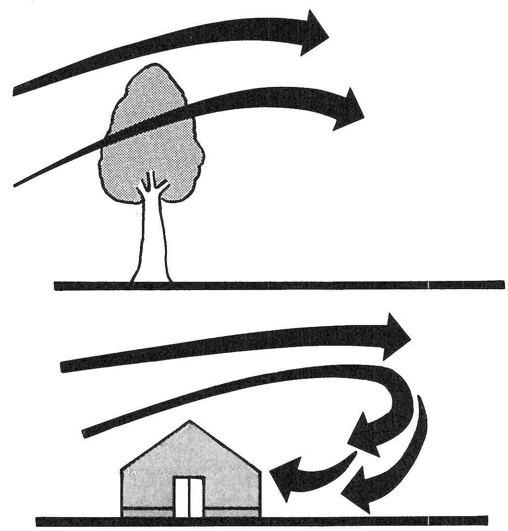


Fig. 5.A.2. Porous windbreaks are better than solid windbreaks as they reduce downdraft effects.

A good, well-planned tree windbreak will reduce wind velocities for 10 to 30 tree heights downwind. A tree windbreak has added advantages in being inexpensive, long-lived, and requiring little maintenance. To construct such a windbreak, one should first sketch the present layout allowing for future business expansion. To avoid light interference problems, trees should not be planted closer than four times the expected mature tree height. The best zone of protection is four to six mature tree-heights downwind from the windbreak where the wind force is broken by approximately 50 percent (Fig. 5.A.3.).

The most effective windbreaks consist of a mixture of four to five rows of deciduous and coniferous (needle) plants planted perpendicular to the prevailing wind. The tree rows should be at least 50 feet longer than the greenhouse area to be protected, as the buffering effect increases the wind velocity 10 to 20 percent higher at the ends of the windbreaks. Planting different kinds of trees guards against losing an entire planting to insects or disease and makes a rough surface for a more effective windbreak.

Before planting, conduct soil tests, cultivate, and

5 miscellaneous methods

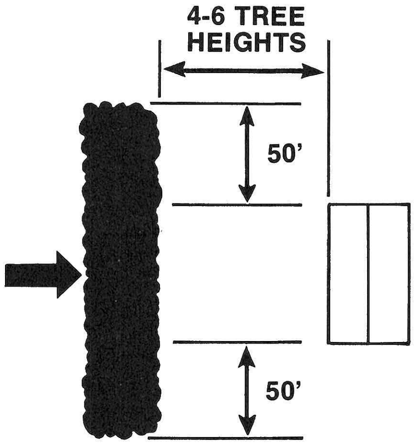


Fig. 5.A.3. Location of windbreak relative to structure for best protection.

fertilize the row strips. If weeds are a problem, proper herbicides may be applied at this time.

The suggested order of planting a five-row windbreak from the prevailing wind direction is as follows: 1) dense shrub, 2) medium-sized, deciduous tree, 3) tall deciduous tree, 4) tall evergreen tree, 5) and medium-sized evergreen.

Dense shrubs — Plant three feet apart in row

Siberian Peashrub, Common Lilac, Tartarian Honeysuckle, Common Privet, Nanking Cherry, Peking Cotoneaster, Japanese Quince, Fragrant Sumac, European Cranberry Bush

Medium-sized deciduous trees — Plant nine feet apart in row

Russian Olive, Golden Willow

Tall deciduous trees — Plant 12 feet apart in row

Black Locust, Green Ash, Honeylocust, Red Maple, Pin Oak, America Linden

Tall evergreen trees — Plant 12 feet apart in row

Ponderosa Pine, Norway Spruce, Douglas Fir, Concolor Fir, White Pine

Medium-sized evergreens — Plant nine feet apart in row

Northern White Cedar, Australian Pine, Scotch Pine, Colorado Spruce

Coniferous trees, in double rows, close-planted and alternately spaced will also provide a good windbreak of 50 percent porosity. Trees should be trimmed at the base up to one-third the height (Fig. 5.A.4.).

Consult your county agricultural Extension agent, Soil Conservation Service or Agricultural Stabilization and Conservation Service for the best plants for your site. They can also help with the design and establishment of the living windbreaks.

In order to get more rapid establishment of the windbreaks, purchase the largest-sized plants that can be afforded from a reputable nursery. However, well fertilized and irrigated small trees will grow very rapidly and start having some effect in about five years.

Although more expensive and requiring more maintenance, fence-type windbreaks may also be constructed and have the advantage of being ready for use immediately. Commercial snow fence, one-inch thick boards, or woven polypropylene netting designed for this service will provide protection. Fifty to 60 percent of the fence structure should be open or porous for best results; however, fences with openings greater than six inches wide will not be effective (Fig. 5.A.5.).

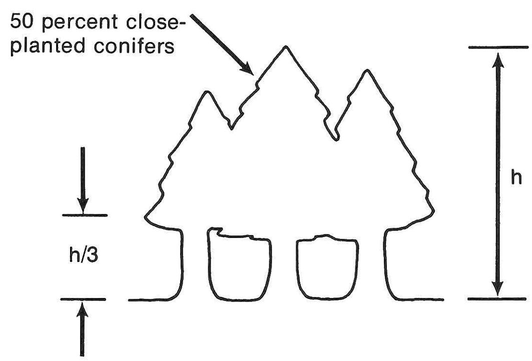


Fig. 5.A.4. Coniferous tree windbreak.

For the typical greenhouse with a ridge height of 11 to 14 feet, a fence height of 10 to 12 feet will give good wind reduction. For best protection, the fence should be located 40 to 60 feet away from the greenhouse on the windward side. Six-inch top diameter posts spaced 10 feet apart and set four feet into the ground are needed to support the fence.

Additional Benefits

1. Windbreaks reduce structural damage resulting from excessive wind pressures during windstorms.
2. By reducing infiltration, windbreaks can increase the effectiveness of added CO_2.
3. Windbreaks can double as snow fences.

5 miscellaneous methods

Caution

1. Do *not* plant windbreaks close to access roads or buildings where drifting snow may cause problems.
2. To avoid shading, do *not* plant windbreaks too close to the greenhouse.

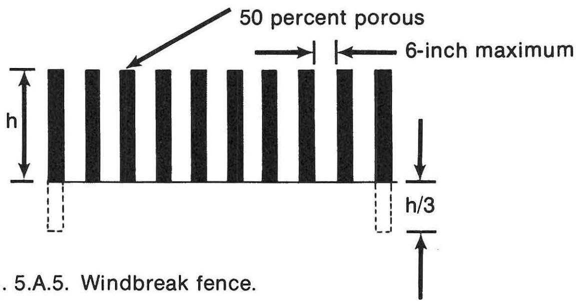


Fig. 5.A.5. Windbreak fence.

Method — Greenhouse Orientation

Possible Action —

The amount of light entering the greenhouse is usually the limiting factor for plant growth and productivity. Therefore, it is important that no external objects, such as trees or buildings, cast shadows onto the greenhouse. The amount of sunlight transmitted through the greenhouse cover to the crop depends on many things, including sun angle, type of covering, and structural design. Orient the greenhouse so that the maximum amount of light is available to the plants (Fig. 5.B.1.).

For a single-span greenhouse the following orientations are best:

1. Above 40° latitude, east to west ridge orientation
2. Below 40° latitude, north to south ridge orientation (Latitude 40° goes through Columbus, Ohio.)

For ridge and furrow greenhouses oriented with east to west ridges, the location of the gutter shadow remains relatively fixed throughout the day. This spot shading causes a corresponding crop reduction. A north to south ridge orientation allows the gutter shadow to sweep across the floor as the sun "moves" across the sky. This reduces spot shading and provides better crop uniformity.

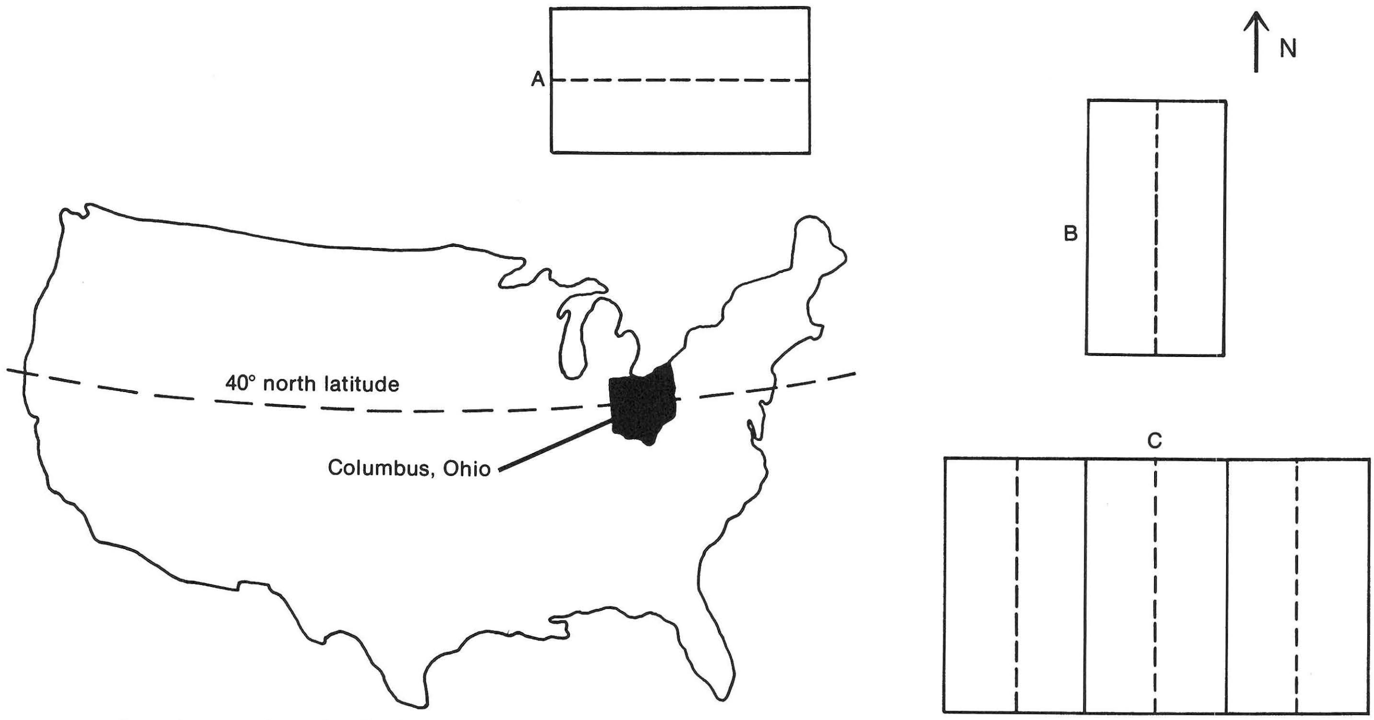


Fig. 5.B.1. Greenhouse orientation for best sunlight control.

A. Single house above 40° latitude. B. Single house below 40° latitude. C. Gutter-connected house at any location.

6 other considerations

Heating Systems

Central or unit space heaters are available for greenhouses (Fig. 6.A.1.). The choice of system depends on the type of fuel available and the amount of greenhouse space to be heated. But other factors are also important. Generally, central heating systems are more economical with greenhouse operations of an acre of more.

Central heating systems, either hot water or steam, require a boiler, valves, and other necessary controls. Heat is transferred to the greenhouse air by either smooth or finned pipes or fan-forced unit heat exchangers. Piping may be perimeter, overhead, between ranges, or beneath benches. Central systems also make it easier to convert from one fuel source to another, a significant consideration with fuel availability problems.

Hot water central systems are generally simpler to install, less complicated, and require less maintenance than a steam system. Hot water system pipes also cool and heat more slowly, but temperatures are normally more uniform. Modulating valves (discussed later) may be easily used with hot water systems to provide accurate temperature control.

Steam provides rapid heating and cooling of the steam lines, and because of the higher temperatures, usually needs less pipe. A steam system requires a high initial investment; however, it has a long life expectancy. Steam heating systems are most often used in large ranges, as steam can be transported efficiently for long distances.

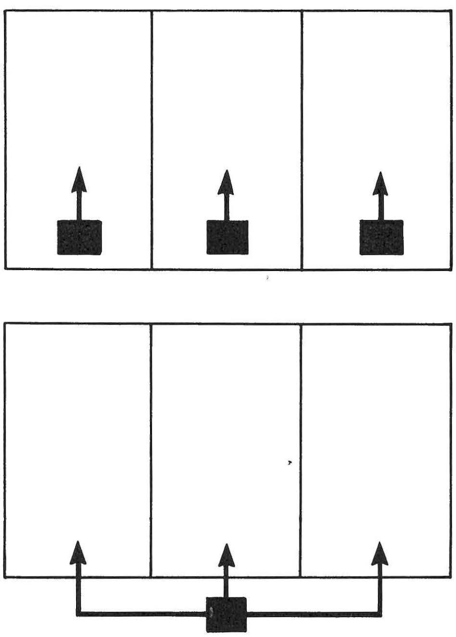


Fig. 6.A.1. Unit heaters versus central heating plant.

Unit space heaters, either mounted overhead or on the floor, are best for small ranges. The unit heater system requires a relatively moderate capital investment, is easy to install, and provides easy expansion of facilities. However, a unit heater system places the heating unit directly in the high-humidity greenhouse environment, which tends to shorten the life of the unit. Unit heaters use fans for heat distribution and are normally fueled with natural or bottled gas or fuel oil. This requires that combustion air be vented into the greenhouse and combustion by-products be vented outside. The cool incoming combustion air should be heated to maintain burner efficiency and protect the plants. Additional heat for the greenhouse is required because the unit vent stack is always drawing warm air out of the house whether the unit is burning or not. Leaking fuel lines, lack of adequate combustion air, or the use of unvented or improperly vented heaters may result in fumes harmful to plants and workers.

Unit heaters are usually rated in Btu per hour. Hot water or steam boilers may be rated by square feet of equivalent direct radiation (EDR), boiler horsepower, linear feet of pipe, and Btu per hour. These terms are related as shown:

1 sq. ft. EDR (steam) = 240 Btu per hour (based on a steam temperature of 215°F and room air at 70°F, correction factors needed for other conditions).

1 sq. ft. EDR (hot water) = 150 Btu per hour (based on a water temperature of 170°F and room air at 65°F, correction factors needed for other conditions).

1 boiler horsepower — 33,475 Btu per hour

1 boiler horsepower — 139.5 sq. ft. EDR, steam

1 boiler horsepower — 223 sq. ft. EDR, water

The term *boiler horsepower* was originally adopted by boiler manufacturers as a convenient means of rating boilers and has no connection with engine horsepower.

Heat Distribution

Heat is usually distributed by either forced air circulation (forced convection) methods from unit heat exchangers or heaters or by natural air circulation (natural convection) from heated pipes. Any heating system should be designed to distribute heat evenly and encourage uniform crop growth.

Piped heat-distribution systems may use plain or finned pipes. Finned piping provides more efficient heat transfer because of the increased surface area exposed. For example, a 1¼-inch bare steel steam pipe with a 145°F temperature difference between inside and out will deliver about 164 Btu per hour per foot of pipe. A 1¼-inch aluminum finned pipe (available from greenhouse suppliers) under the same conditions is rated at 1,440 Btu per hour per foot of pipe or eight to nine times as much heat transfer per foot of pipe. However, in some cases bare steel pipe may be desirable. On long pipe runs, the slower heat transfer will provide more uniform temperatures along the length of the greenhouse.

A system for forced-air circulation helps to maintain optimum levels of temperature and humidity and satisfactory levels of carbon dioxide at leaf surfaces. This makes for healthier plant growth and, more important for plants with dense foliage, fewer problems with diseases associated with high humidities.

Perforated poly-tube or fan-jet systems are frequently used to provide more uniform heat distribution, air movement and ventilation in greenhouses using any of the previously mentioned heating systems. However, they are most frequently installed in conjunction with unit heaters or unit heat exchangers.

Heating System Controls

One should select and install quality controls to maintain temperatures within adequate tolerances. The best heating system will have minimal value, if its controls do not work properly. Temperatures below the optimum level cause reduced productivity and delayed crop maturity with subsequent market losses. Temperatures above the optimum waste energy. For example, with an outside air temperature of 40°F, a greenhouse maintained at 62°F will use 10 percent more fuel than the same house maintained at 60°F.

Two basic types of control systems are *on-off* and *proportional.* On-off systems maintain the temperature between two extremes, with the desired temperature usually midway between the extremes. Heat is not supplied until the temperature falls to the lower extreme. Once activated, heat is supplied until the upper temperature extreme is reached. With this system, the temperature always varies between the extremes, and the degree of control depends on the range built into the thermostat. To minimize this temperature variation, select a thermostat with a ±1°F control range (specified as 1°F differential).

A disadvantage of on-off systems is the possibility of thermal shock. A sudden flow of hot water or steam into cold pipes may cause the pipes to jump off their supports. Also, the sudden opening of many valves at once can damage a boiler by suddenly replacing the hot water with cold water. However, some types of heating systems, such as unit heaters, can be controlled best by on-off controls.

The other control system is the proportional (modulating) type. The amount of heat supplied to the greenhouse depends on how far below the desired level the temperature has fallen. The greater the difference between the actual and the desired temperature, the wider the valve is opened and the more heat is supplied. These control systems can maintain temperatures at close tolerances and are energy efficient. Although these systems provide better control, they are slightly more complicated and more expensive than on-off systems.

Energy Sources

Fuel energy content is measured in *British thermal units* (Btu). One Btu is the heat energy required to raise the temperature of one pound of water one degree Fahrenheit (at 39.2°F). One *therm* is equal to 100,000 Btu which is also equal to the energy content of 100 cubic feet of natural gas. The energy content of different energy sources is listed in Table 6.B.1.

All energy sources have advantages and disadvantages as listed below:

1. Natural gas — one of the most economical fuels but price subject to political manipulation and availability problems. It needs no on site storage, and supplying it to the burner is simple. Natural gas may be used in a central boiler or remote unit heaters and is a clean-burning fuel that requires little equipment maintenance.
2. Propane — a very clean fuel, but as a derivative of natural gas its availability is questionable. It is usually expensive but is easy to supply to the burner, and maintenance is minimal. Propane may be used in central boiler or remote unit heaters, but adequate storage facilities are required.
3. No. 2 oil — a more expensive but relatively clean fuel. It may be stockpiled but requires expensive storage tanks; otherwise its availability is questionable. Equipment maintenance is slightly more demanding than with gaseous fuels.
4. No. 6 oil — similar in price per Btu to No. 2 oil. It is a dirty fuel that requires preheating and special attention to equipment for effective systems. Oil may be stockpiled. Expensive storage tanks are required.
5. Coal — a very dirty fuel requiring regular daily maintenance for efficient operation. Ash removal and disposal are also necessary. Low grades may require expensive stack pollution-control equipment. Coal may be eas-

ily stockpiled in the open if space is available. Its availability is subject to mining and transportation strikes. Use of coal is limited to central heating plans.

6. Electricity — in most locations, a relatively expensive energy but clean. Electric heaters do not require chimneys or combustion air inlets, and heaters may be easily placed anywhere. Electricity cannot be stockpiled, but it is 100 percent efficient for the user.

Conversion Efficiencies

When a fuel is burned for heating, generally not all of the heat energy of the fuel is recovered. This loss usually has three modes (Fig. 6.B.1.):

1. Incomplete combustion: too much or too little air makes the fuel burn improperly, and not all of the fuel is converted to a hot gas.
2. Incomplete heat exchange: dirty surfaces which act as insulation can reduce the heat exchange effectiveness. In a boiler, heat exchanger "dirt" may be soot on the fire side or scale on the water side from minerals in the water. The energy in the hot gas not transferred in a heat exchanger to air or water is lost up the stack. (This heat serves to carry off harmful combustion gases.)
3. Losses between heat exchanger and heat distribution system: if the heater is located in an unheated space and heat is lost through the heat exchanger exterior, the efficiency of a heater may be reduced. With central boiler systems this occurs when heat is lost from the water through the exterior boiler jacket. Part of this heat can be recovered by using it to warm incoming combustion air, allowing a hotter, more efficient flame.

Related to the first two forms of energy loss are these corresponding efficiencies:

1. Combustion efficiency: relates only to the effectiveness of the burner and its ability to burn the fuel completely.
2. Thermal efficiency: a measure of the effectiveness of the heat transfer in a heat exchanger. Does not take into account heat losses from the boiler jacket or other losses like the variance of fuel heating values.

Fuel-to-steam or service efficiency accounts for all boiler heat losses and depends on the burner effectiveness and the temperature of the exhaust gases leaving the boiler. It is calculated as the ratio of Btu output divided by Btu input and is the correct efficiency to use in determining and comparing fuel costs.

Boiler efficiency is a general term sometimes used to indicate thermal or fuel-to-steam efficiency. If an

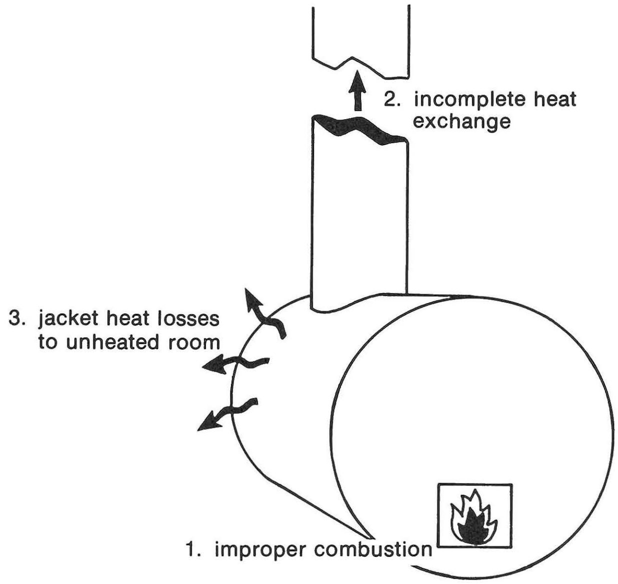


Fig. 6.B.1. Modes of boiler heat loss.

efficiency value is not listed on the device, usually the Btu input (fuel usage) and Btu output are. Efficiency may then be found by dividing the Btu output by the Btu input.

Table 6.B.1. shows conversion efficiencies with optimum and with more typical operating conditions (dirty flues, etc.). Figure 6.B.2. shows the cost to supply 100,000 Btu of heat from different energy sources. These costs represent a price range based on the two conversion efficiencies. For example, natural gas costing the grower $2.50 per 1,000 cubic feet will, with optimum conversion conditions (80 percent efficient), provide 100,000 Btu at a cost of 31¢. At the same cost per cubic foot but under more typical conditions (70 percent efficient), it will cost 36¢ to provide 100,000 BTU. By maintaining his equipment properly the grower can save 5¢ per 100,000 Btu of heat required.

Cost Comparisons

As different energy sources have varying quantities of heat available per unit, and because units and conversion efficiencies vary, cost comparisons should be made on a cost per 100,000 Btu basis. Comparing different energy sources in this way will demonstrate which energy is the most economical.

The choice of an energy source for greenhouse heating has been mostly a matter of economics. In the future, however, fuel availability may be a more important consideration. To minimize this risk, many growers install boilers that can burn more than one type of fuel. If dual fuel capability is not possible, sometimes another boiler is used to handle an alternative fuel. These methods are most effective, if the grower first minimizes his energy use by adopting sound energy conservation practices and properly maintaining his structure and equipment.

TABLE 6.B.1. Heat values and conversion efficiencies for different energy sources.

Fuel	Efficiency Maximum	Efficiency Typical	Heat Value
Coal, hard (anthracite)	70	50	13,000 Btu/lb.
soft (bituminous)	70	50	11,400 Btu/lb.
Natural Gas	80	70	1,000 Btu/cu. ft.
Propane	80	70	85,000 Btu/gal.
Fuel Oil (No. 2)	80	65	140,000 Btu/gal.
(No. 6)	80	65	150,000 Btu/gal.
Electricity	100	100	3,413 Btu/kw. hr.

Compare fuel costs between greenhouses to evaluate your energy management policies against other growers. Providing the greenhouses are of the same construction, in similar condition, and using the same fuel, fuel costs may be directly compared on a square foot of floor area basis:

$$\frac{\text{annual fuel cost}}{\text{total greenhouse floor area}} = \frac{\$}{\text{sq. ft.}}$$

Similar greenhouses with similar conditions but using different fuels may be compared on a Btu-per-sq.-ft. basis by referring back to Table 6.B.1.

$$\left(\frac{\text{annual fuel cost}}{\text{total greenhouse floor area}}\right) \times \left(\frac{1}{\text{cost per fuel unit}}\right) \times \left(\frac{\text{Btu}}{\text{fuel unit}}\right) = \frac{\text{Btu}}{\text{sq. ft.-yr.}}$$

The grower knows his annual fuel cost, cost per fuel unit ($/gal., $/lb. etc.) and greenhouse square footage.

For example, a grower with a one-acre house (43,560 sq. ft.) heated with natural gas costing $2.50/1,000 cu. ft. has an annual fuel bill of $35,000. From Table 6.B.1., there are 1,000 Btu per cu. ft. of natural gas. Then:

$$\left(\frac{\$35{,}000/\text{yr.}}{43{,}560 \text{ sq. ft.}}\right) \times \left(\frac{1{,}000 \text{ cu. ft. of gas}}{\$2.50}\right) \times \left(\frac{1{,}000 \text{ Btu}}{1 \text{ cu. ft. of gas}}\right) = 321{,}400 \ \frac{\text{Btu}}{\text{sq. ft.-yr.}}$$

Ventilation

Greenhouses need ventilation to maintain optimum plant growth temperatures and humidities, and in greenhouses without supplemental sources of CO_2, adequate carbon dioxide levels. Ventilation requirements depend on plant and weather conditions and vary according to time and season.

Ventilation reduces high temperatures caused by absorbed solar radiation. A greenhouse in Ohio on a sunny summer day may have a solar radiation input of 300 Btu/hr. per square foot of floor area. This solar

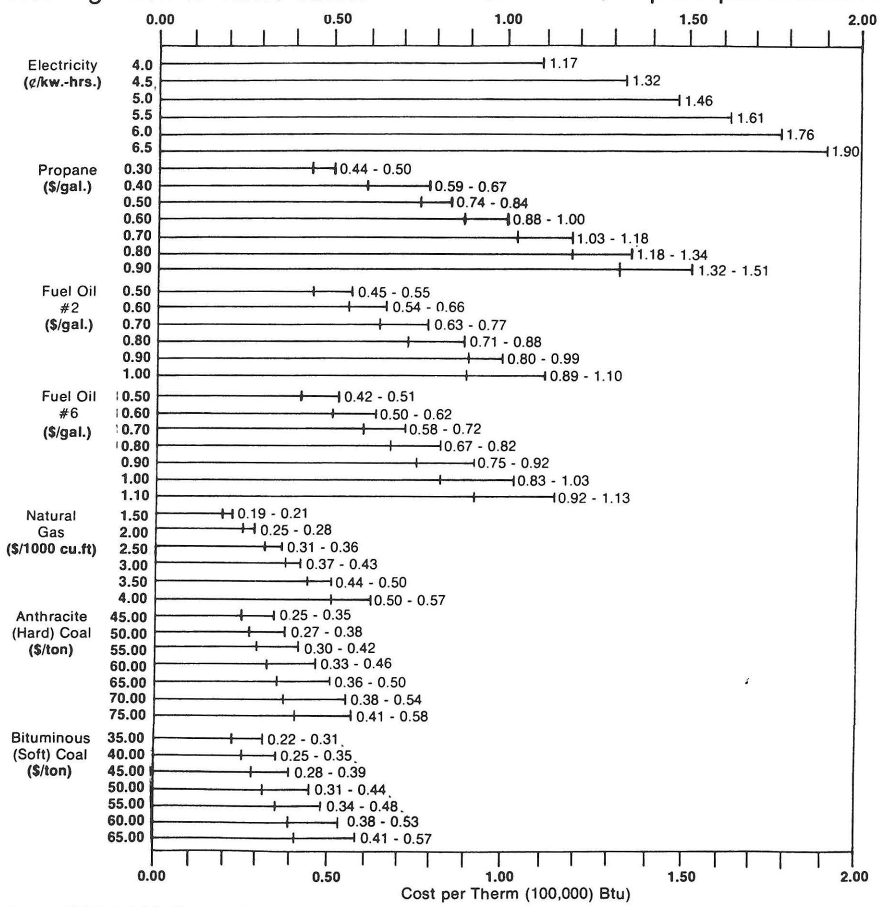


Fig. 6.B.2. Cost ($/100,000 Btu) of heat output as supplied from different energy sources. Cost range for optimum and more typical conversion efficiencies indicated are based on Table 1.E.1.

energy input will cause a greenhouse air temperature rise depending upon the rate of heat loss from the structure and the amount of energy absorbed within. Objects inside the greenhouse, such as benches, will absorb and store energy as the temperature increases. The more mass to absorb energy, the slower the temperature will rise. At night when the air temperature falls below that of the objects, the stored heat flows back into the air and helps to heat the greenhouse.

Plants will reduce the air temperature rise substantially by transpiring water, an evaporative process. Because evaporation requires energy to change liquid water to vapor, it cools the air as it extracts energy from the air and adds water vapor. Thus, a greenhouse filled with a well-watered crop will have half the cooling requirements as the same greenhouse without a crop and with dry soil.

One method of cooling is to employ shading that will absorb the solar radiation at or outside the greenhouse surface by covering the greenhouse with screen cloths or wood lath blankets or, as more frequently used, by spraying a "white-wash" shading mixture on the exterior. Although these methods are energy-efficient, they reduce the light available for photosynthesis and are restricted to crops that can tolerate lower light levels.

Either natural or forced ventilation can remove excessive heat from the greenhouse. Natural methods use heat or wind pressure differences while forced ventilation methods use mechanical means, such as fans, to move air.

Effective natural ventilation systems employ ridge and opposite sidewall vents which run the full length of the greenhouse (Fig. 6.C.1.). Solar energy, absorbed by the plants and soil, heats the greenhouse air which rises and escapes out the ridge vents while cool makeup air enters the sidewall vents. For most effective natural ventilation, the area of the ridge vents should be 25 percent of the floor area, as should the area of both side vents. Also, for ridge vents hinged at the top, the vent and roof should form a 60-degree angle when fully open. Greenhouses which have only side vents depend on wind pressure to force air exchange and are usually ineffective.

Natural ventilation requires no cooling equipment and, if not automated, no electric power. The disadvantages include increased infiltration, difficulty in obtaining proper control, and insufficient pressures for operating evaporative pad cooling systems. Also, natural ventilation systems do not always provide uniform cooling or satisfactory air flow through the plants. Care must also be taken during winter ventilation to warm cold makeup air adequately before it reaches the plants.

Forced-air ventilation systems provide more uniform air flow to the plants, more accurate temperature control, and enough force for evaporative pad cooling systems. Properly designed forced-air sys-

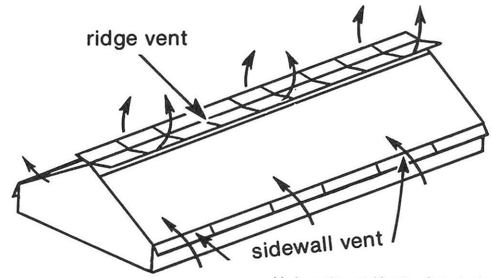


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Fig. 6.C.1 Natural ventilation with ride and sidewall vents.

tems will assure adequate air movement through the vegetation and in winter can effectively mix and warm cold makeup air before circulating it to the plants. The construction of some greenhouses, such as double plastic covered houses, makes the installation of ridge vents difficult and the use of forced-air systems necessary.

For warm weather cooling, locate exhaust fans on one side or endwall and inlet air openings on the opposite side or endwall. As the air flows through the greenhouse, it absorbs heat and increases temperature. The rate of rise can be controlled by increasing the air flow rate (which consumes more power) or by limiting the distance between air inlet and exhaust openings. An air exchange rate of one greenhouse volume per minute will limit the temperature rise to 10°F and will be most energy efficient. The distance between air inlet and outlet must not exceed 225 feet and, to be most effective, should not exceed 125 feet.

Under some conditions, particularly high outside air temperatures, ventilating with outside air will not provide adequate cooling. Using supplemental mechanical refrigeration is expensive at the high heat loads and also dehumidifies the air. Low humidities under high light conditions increase the water loss from plants and increase the probability of wilting. For these reasons, most greenhouses use evaporative cooling systems which economically cool and humidify the air.

Evaporative cooling systems are constructed by covering the air inlet with a porous, wet pad (Fig. 7.C.2.). The pad, either mounted horizontally or vertically, provides wetted surfaces for the incoming air to contact without having a complete water film across the opening that would block air flow. Pad materials are aspen fiber or rubberized hog hair contained in welded wire mesh or, more recently, rigid cellulose paper pads.

Vertical pads have a perforated-pipe, distribution header across the top and a gutter-type catch basin beneath to catch the water for recycling. Vertical pads constructed with aspen or rubberized hog hair require much maintenance to keep them effective. These pads tend to settle, leaving holes for uncooled air to pass, or they degrade, causing problems with water recycling. Water treatment with algaecides is helpful, but the chemicals may be lost if rain water overflows the sump. The new rigid cellulose pad materials eliminate most degradation and settling problems.

Horizontal pads have been developed as low cost cooling systems. Their main disadvantage is that they require more floor space than vertical pads. This can be minimized by stacking an equivalent area of smaller horizontal pads. The open top of the horizontal pad is an advantage because it simplifies

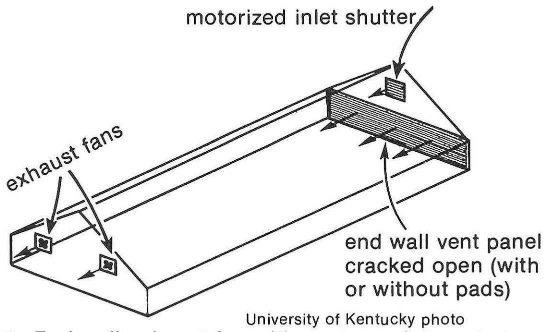

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Fig. 6.C.2. End wall exhaust fan with vent panel or pads in opposite wall and/or motorized shutter(s).

pad repair. Horizontal pads use mist nozzles to spray water, and, if designed properly, do not require water recycling systems. These advantages simplify maintenance and make horizontal pads energy efficient.

Regardless of the method of cooling used, the ventilation fans must be properly sized, located, and controlled, and adequate air inlet area provided for efficient cooling. A few large-diameter fans are more energy efficient than several small fans. However, a number of small fans can be spaced to provide more uniform air flow, and the air flow rate (and temperature rise) can be more easily controlled.

Fans should be located to face downwind if possible. When fans must face into the prevailing winds, purchase and install fans with CFM capacity 10 to 15 percent greater than calculated, and similarly, increase the motor horsepower ratings of these fans.

Control fans with a thermostat that is shaded from the sun and has a small blower circulating air across it (aspirator). The simplest type of control system is an on-off system. If the temperature reaches the set value, the fans and pads come on until the temperature falls below the set point. Although inexpensive, on-off control capabilities are limited.

A more complicated and expensive system is the proportional (modulating) type. The control circuit is constantly comparing the desired temperature with the actual temperature. The greater the differences between the desired value and the actual temperature, the more corrective action is taken to reach the desired value. With a ventilation system, the controlling circuit may speed up or slow down the fans to maintain a precise temperature.

Between these two control systems is the staged system. This system uses the simplicity of on-off controls to approximate inexpensively the proportional control system. By using a number of fans, more fans and the evaporative pad system can be turned on in stages as the temperature increases. To provide uniform air flow, staged fans should be separated, so that only one out of a group of three are on initially. Others located in between are switched on as the temperature rises and shut off in reverse sequence as the temperature falls. Fans should not be spaced more than 25 feet apart to assure adequate air distribution.

Fans are rated on the basis of the static pressure for a given volume of air moved. Propeller-type fans which move large volumes of air against low static pressures efficiently are the best for most greenhouse applications. Select fans with specifications based on tests by the Air Moving and Conditioning Association bearing the AMCA seal of approval to assure dependable and comparable information.

Choose a fan that will deliver the required air volume at the expected static pressure with the minimum horsepower. Values of 0.10-0.15 inch of water static pressure are normally used for sizing greenhouse fans unless the fans will be used with an evaporative pad cooling system. Pressure drops associated with an evaporative pad should be obtained from the pad manufacturer. The volume of air to be moved is simply the number of air changes per minute multiplied by the greenhouse volume. Fans should be sized for one air change per minute (10 cfm per square foot of floor) for summer ventilation and for 0.3-0.4 air changes per minute (3-4 cfm per square foot of floor) for winter ventilation. Undersized fans will not effectively control the environment, and oversized fans will result in higher operating costs, higher initial investment, and excessive air velocities. Air velocities across the plants of more than 200 feet per minute have an increasing negative effect on plant growth.

Fans will be most energy efficient if the motors are not oversized and are of energy efficient design. Such recently developed motors now on the market have a slightly higher initial cost but will easily repay the increased investment over the life of the motor. If three-phase electric power is available in the greenhouse, three-phase motors should be used because they are cheaper and require less maintenance than single-phase motors.

To minimize power requirements, select the largest diameter fan at the slowest speed that will still meet the air flow and static pressure requirements. However, as mentioned previously, greenhouse conditions may make it desirable to select and locate a number of smaller fans to provide more uniform air distribution and easier control. Two-speed fans may also be used effectively in some situations. Fans mounted in "bell-mouthed" housings will give slightly increased air delivery at no extra power input in comparison with fans mounted in flat "diaphragm" housings (Fig. 6.C.3.).

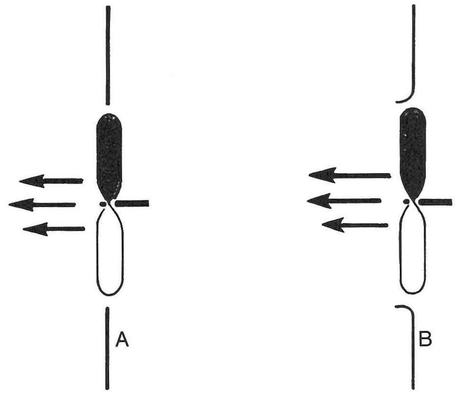


Fig. 6.C.3. Propeller-type fan mounted in flat (A) and "bell mouth" (B) housing.

Baffles minimize air flow requirements by channeling available air flow through the plants. Skirts around benches prevent unnecessary air exchange of air beneath benches, and transparent baffles placed overhead will reduce air exchange in the area above the crop zone.

The total air inlet opening in the wall should provide approximately 1.5 square feet per 1,000 cfm of fan capacity. To prevent air exchange when the fans are off, outlets of exhaust fans should be fitted with shutters that open easily when the fan starts. Shutters on air inlets should be motorized and wired into the fan control system. Shutter blades should be linked together and have nylon or brass bearings to provide maintenance-free operation.

A greenhouse with powered ventilation will have a slight vacuum inside. Openings in the exterior of the greenhouse will leak air and, depending on the size and locations of leaks, may provide insufficient or no air flow through the plants or cooling pad. Greenhouses in good repair will be the most efficient — unless doors and vents are unnecessarily left open.

Misting Systems

Some cooling systems use fine water droplets. These methods are most appealing for plant propagation, which requires high humidities and more uniform cooling than provided by non-misted systems. To be effective, most mist systems require high water pressures (150 to 200 psi) to provide small droplets that will evaporate before reaching the ground. Free water on the plants may cause disease problems or blossom discoloration. However, depending on nozzle spacing and steadiness of water pressure, mist systems may not provide satisfactory cooling uniformity.

Fog eliminates free water problems and provides adequate cooling uniformity and humidity. Past attempts at generating fog have usually been troubled with nozzle clogging. Recently developed systems minimize this problem by using high pressure air (60 to 80 psi) with low pressure water, which allows use of a large nozzle. Spinner nozzles capable of providing fine water droplets with low water pressures are also available.

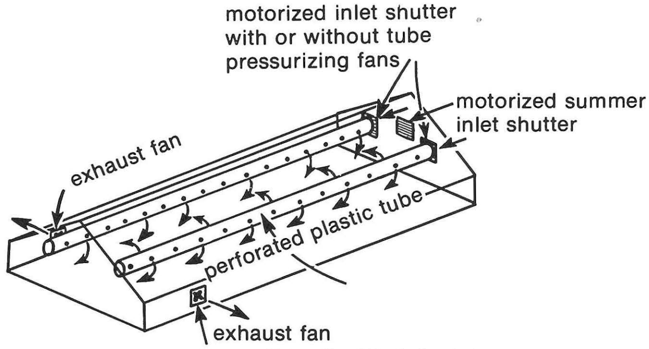
One problem common to mist and fog systems is that minerals carried in the water are released on evaporation, coating and discoloring plant surfaces. On the positive side, neither system requires fans to operate effectively.

Winter Ventilation

Winter ventilation is required primarily for two reasons: (1) to dump excess heat on sunny days, and (2) to control humidity in the greenhouse. Control of relative humidity is most important, as a relative humidity below 70 percent will increase transpiration from the plants and require more irrigation. If inadequately watered, especially in sunny weather, plants may wilt, indicating a loss of plant productivity.

To control humidity during winter, small amounts of cool, low-moisture-content outside air is brought in while venting warm moist air to the outside. Older, leaky greenhouses exchange air through infiltration and naturally control greenhouse humidities. However, the use of newer, tighter construction techniques, such as the double plastic-covered greenhouse, and the adoption of energy conservation practices has reduced infiltration and made humidity control necessary. Venting to control humidity consumes energy because of the need to heat the incoming air and the fact that warm air and moisture are "lost" outside. A properly functioning humidistat control system combined with a good air-mixing and distribution system will minimize the amount of air exchange and energy consumption necessary for humidity control.

Air distribution systems should introduce cold air high into the greenhouse, effectively heat the cold air by mixing with warm air, and circulate the warmed air uniformly within the greenhouse. Fans circulating air through perforated poly tubing are quite effective for this application (Fig. 6.C.4.). For



University of Kentucky photo

Fig. 6.C.4 Overheat perforated plastic tubes with or without pressurizing fans, end-wall motorized inlet shutters, and exhaust fans mounted in an opposite convenient end or side-wall.

unvented greenhouses, a humidistat should be used to open motorized shutters in front of the poly tube fan and at the same time turn on a low-speed exhaust fan. Vented greenhouses should have the top vent cracked before introducing air through the perforated poly tube.

Humidity control is difficult during fall and spring when outside temperatures and humidities are similar to those inside the greenhouse. In the damp, cloudy weather of these seasons, high humidity can be controlled best by heating the greenhouse for a short time, even though optimum plant temperatures may be exceeded. Heating the air will increase its moisture-holding capacity and lower its relative humidity.

Ventilation and Air Circulation for CO_2 Control

Photosynthetic activity by plants confined in a greenhouse can greatly depress CO_2 levels even with the greenhouse vents partially open. Supplemental CO_2 can be added to unvented greenhouses to maintain adequate CO_2 levels but usually cannot be added effectively to vented greenhouses (see section on CO_2 enrichment). Vented greenhouses, particularly in summer, can at least partially compensate for depressed CO_2 levels by increasing the air flow rate across the leaves. For instance, research has shown that plants provided with 200 ppm CO_2 at an air flow rate of 100 feet per minute gave equivalent growth to plants in still air at the normal air 300 ppm CO_2.

Artificial Lighting

Artificial lighting for growing plants may supplement the intensity (photosynthetic energy) of natural light, provide day length (photoperiod) control, or control the physical formation of the plant through regulation of the amount, quality, and timing of light applications (photomorphogenesis).

Plants use radiant (light) energy as the principal source of energy for plant growth (Fig. 6.D.1.). The intensity of light available to a plant determines the rate of photosynthesis if other factors are not limiting. Plants will increase the rate of photosynthesis with increasing light intensity until a saturation point is reached at which additional light will not affect photosynthesis. The saturation point for most crops is usually well above the economical limits of providing supplemental light. Although other conditions are important for photosynthesis, light is usually considered the most important and the most difficult or costly to obtain.

The two most important requirements for economical plant production are maximum use of space and minimum time of occupancy. During winter, when heating costs are highest, low light levels may dictate a slow growth rate. For some

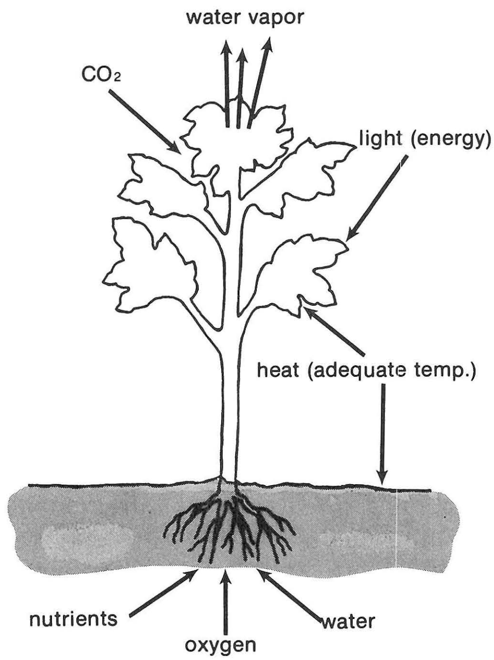


Fig. 6.D.1. Conditions necessary for plant growth.

crops, proper supplemental lighting can increase quality and yield of plants and decrease time of occupancy by hastening maturity. Natural lighting throughout the winter is also highly irregular and unpredictable. The addition of supplemental light to maintain a standard minimum light level can greatly aid in planning and marketing of crops by precisely scheduling maturity dates.

Light Criteria and Lamp Selection

Artificial light is generally produced by converting electrical energy to radiant energy by using a lamp.* A radiating body such as the sun or a lamp produces a spectrum of radiation (Fig. 6.D.2.) which varies in wavelength and frequency. Usually, plants use radiation from 400 to 700 nanometers (nm) in wavelength for photosynthesis, a range which essentially corresponds to visible radiation. The radiation in this 400 to 700 nm range is ordinarily defined as photosynthetically active radiation (PAR), although plants may also use non-visible radiation to a certain extent.

The amount of useful radiation (PAR) produced per watt of electrical power consumed determines the efficiency of an electric lamp. Various types of electrical lamps have different efficiencies, spectral distributions, and useful lives (Table 6.D.1.). The spectral distribution for a given lamp may be quite broad or concentrated at certain wavelengths. By selecting the most efficient lamp that will provide the necessary light intensity and spectral distribu-

*Lamp: a source of visible radiant (light) energy. (Although non-visible radiation may also be produced by a radiation source, visible radiation must be produced by the radiation source before the radiation source is called a lamp).

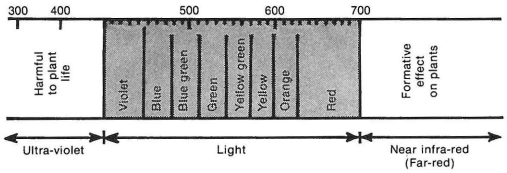


Fig. 6.D.2. The visible and near-visible radiations of the electro-magnetic spectrum.

tion, electricity use can be kept to a minimum. Fortunately, it is usually quite rare for one plant species or variety to respond to one lamp differently than another, except when sunlight is excluded.

One should also select lamps with higher power ratings whenever possible, because they are generally more efficient than lower power rated lamps. For example, a 15-watt lamp will produce fewer lumens* per watt than one rated at 100 watts. Likewise, it is better to use one large lamp instead of two equivalent wattage small ones. As an example, one 150-watt incandescent bulb delivers 2,880 lumens while two 75-watt incandescent bulbs deliver only 2,380 lumens.

TABLE 6.D.1 Typical efficiencies for different types of lamps.

Lamp Type	Output
Incandescent	19 lumens/watt
Mercury vapor	57 lumens/watt
Fluorescent	75 lumens/watt
High pressure sodium (yellow)	140 lumens/watt
Low pressure sodium (orange)	183 lumens/watt

(From "Sun Earth," Charles Scribner's Son, NY, 1976).

Aside from spectral and efficiency information, the criteria for lamp selection include physical size, radiation intensity per unit area, and whether a lineal or point source of light (Fig. 6.D.3.). Intensity may be controlled somewhat by adjusting the distance between lamps and crop or by using reflectors. The type of application is also important. For example, lamps and fittings used to supplement natural sunlight should be as compact as possible to minimize shading. (This is usually accomplished by selecting high-powered lamps with internal reflectors or, if lamps of this type are unavailable or unsatisfactory, using compact external reflectors with appropriate lamps). Fixtures and reflectors should be designed to direct and deliver the maximum possible useful light. In summary, select the most efficient lamp fixtures and reflectors that will best meet the requirements of the crop and application.

Efficient Lamp Installation

For most efficient use, arrange lamps in rectangular block layouts instead of in narrow rows or benches. This arrangement increases the likelihood that higher-powered, more-efficient lamps can be used and minimizes wasteful light overspill.

Lighting must be uniform to assure crop uniformity. Lamps should be spaced horizontally and vertically to provide no more than a $\pm 10\%$ variation in illuminance** unless used only for photoperiod control. Photoperiod control requires that all plants receive a set minimum level of light with the level dependent on the crop. As long as all plants receive this minimum, variations above this level will have no effect.

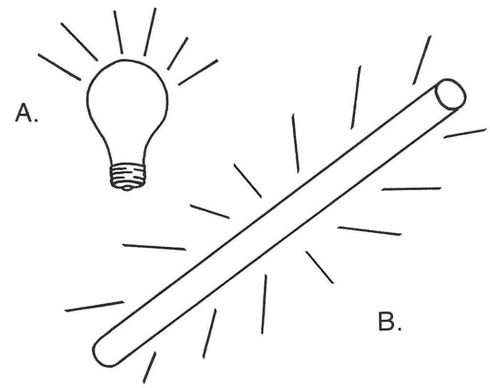


Fig. 6.D.3. Point (A) and lineal (B) source lamps.

Light output, along with fixture design and surface reflectivity of objects within the greenhouse, affects the amount of useful light striking a surface. Paint greenhouse interiors light colors to increase available light. Dark-colored surfaces will absorb light which could have been reflected and used for illumination.

Efficient Lamp Operation

For the most economical operation, use the lamp at its rated voltage. Operating a lamp at a lower voltage than specified will prolong its life but reduce its light output. However, if a bulb is in an inaccessible location where maintenance costs are high, it may be more economical to oversize the lamp and operate it at a lower-than-rated voltage to reduce maintenance costs.

Incandescent lamps deteriorate according to total operating time and should be turned off whenever not needed. The electrical discharge types of lights that require starters and ballasts (fluorescent, mercury vapor, metal halide, sodium vapor) are "ignited" by bursts of extremely high voltage, and lamp and ballast life are decreased slightly each time the lamp is started. The shortened lamp life caused by starting more than once during a 15-minute period will more than offset any electricity saved.

Lamps and associated ballasts (automatic lamp current controllers) will give off tremendous amounts of heat when operating (Table 6.D.2.). For example, the most efficient lamp — the low pressure sodium lamp — will have only 27 percent of the total

* Lumens (luminous flux): time rate of flow of light energy.

** Illuminance: the time rate of flow of light energy (lumens) intercepted per unit area.

input power given off as visible radiation; 28 percent will be non-visible radiation, 26 percent conduction/convection heat losses, and 22 percent ballast heat loss. However, the total input power to a lamp is essentially converted to heat because for most light sources, the plants will use less than one percent of the radiation for photosynthesis. The remaining radiation will be absorbed by the plants or objects in the greenhouse and converted to heat. Depending on the type and quantity of lights needed for a particular application, heat from the lamps may create excessive plant temperatures. For growth chambers in particular, it is usually economically feasible to find alternate uses or to remove and store the surplus heat for later.

TABLE 6.D.2. Effectiveness of high pressure sodium luminaires (1000 W) in providing greenhouse heating*.

Intensity ft.-c	Lamp loading W/ft.^{2}	Lamp spacing** ft.	Increase in temp. (°F) with air leakage of: (volumes per hour) 1	2	4
250	3.4	17.1	8	7	6
500	6.8	12.1	16	13	10
1000	13.8	8.5	31	26	21
1500	20.4	7.0	46	40	31

* From: Norton, R.A. 1977. Commercial Lighting of Bedding Plants. Proc. of 10th Int. BPI Conf., pp. 73-80.

** To obtain mounting height, multiply by 1.3.

Lamp Maintenance

A regular maintenance program is essential to efficient lighting practice. Lamps and reflectors should be kept clean to allow maximum light output. The procedure for lamp replacement is also important. To maintain consistent plant growth and minimize lamp replacement labor, all lamps should be: a) replaced as they fail and b) completely replaced in bulk at the end of their rated service life.

The rated service (operating) life of a lamp is a statistically derived average which means that some lamps will fail before and others after this time has lapsed. Light output also falls progressively with time. Because of the method of construction and operation of electric discharge lamps, early failure is less likely, and many will continue to provide light long after the point where light output ceases to be economical.

Any lamp that fails should be replaced immediately, at the same time marking the new lamp in order to identify it. All lamps should be replaced as a batch when their rated service life has been reached. Any marked lamps, then removed, should be put aside and retained for replacing early failures in the next batch.

Other Lighting Considerations

Make the best use of natural sunlight before adding supplemental light. Select roofing materials with high sunlight-transmission characteristics. Be sure the cooling system is adequate to minimize the need for shading. Apply shading only when required to keep temperatures down.

Carbon Dioxide Enrichment

In photosynthesis, plants use nutrients and sunlight to manufacture sugars and provide growth. The rate of photosynthesis is governed by available nutrients (including water), carbon dioxide (CO_2), light, and temperature (Fig. 6.D.1.). The ultimate rate is determined by the factor in least supply (limiting factor).

Under normal conditions, CO_2 exists as a gas in the atmosphere at a level of 0.03 percent or 300 ppm (parts per million). During the day, when photosynthesis occurs in the presence of sunlight, the plants in a greenhouse may reduce the level of CO_2 to 150 to 200 ppm, or lower. Under these circumstances, CO_2 is made up by infiltration into the greenhouse, and the level of CO_2 may be the limiting factor for plant growth.

The adoption of energy conservation practices to the greenhouse structure usually reduces infiltration and further complicates the problem of CO_2 levels. Some of these energy conservation changes also reduce the amount of light available to the plants and may further limit growth. The addition of supplemental CO_2 can assure adequate CO_2 levels and for some plants partially or fully compensate for lower light intensities.

To a point, increasing CO_2 levels above 300 ppm will increase plant productivity. This can increase plant production per unit of area and/or decrease crop growing time — both important in energy management. All of these elements not only make CO_2 enrichment of the greenhouse atmosphere more important, but in many cases, necessary.

Research data have also shown that, at a fixed light and CO_2 level, higher temperatures can increase photosynthesis and overall plant growth. Thus, higher day temperatures are desirable, as higher temperatures (with increased CO_2 and nutrients) will increase yield and reduce venting, allowing more efficient use of supplemental CO_2 and more storage capability of solar energy. This means that the cooling (not heating) thermostat should be set to a higher temperature (not above 80°F for tomatoes). Also, plants will respond to CO_2 enrichment at below normal temperatures although the response may be less than at normal temperatures.

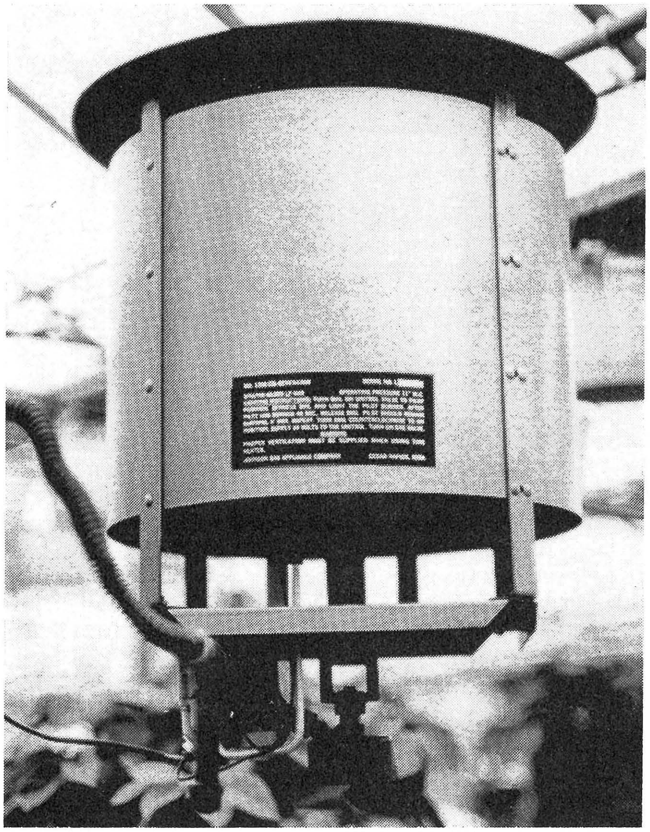


Fig. 6.E.1. One of several available types of open flame, nonvented, within house "heater" CO_2 generators.

The exact CO_2 enrichment level needed for a crop is difficult to pinpoint, as light, temperature, nutrient levels, cultivar, and degree of maturity interrelate. However, commercial growers and researchers usually agree that levels of 1,000 to 2,000 ppm are economically practical for most crops. A concentration of 5,000 ppm is the maximum permissible level beyond which it becomes hazardous to workers. Most plants also have a maximum tolerance level, depending on cultivar.

The CO_2 concentration in a greenhouse environment has been found to vary considerably and depends on several conditions:

1. Concentration difference between the CO_2 inside and outside the greenhouse. The greater the concentration difference, the faster CO_2 will be lost with infiltration air exchange.
2. The tightness of the greenhouse. "Loose" houses have more "open" area which increases infiltration air exchange.
3. External wind speed. Increased wind speed causes greater pressure differences between the inside and outside of the greenhouse and speeds up infiltration air exchange.
4. CO_2 source. CO_2 introduced into the greenhouse at a point will, if cool, diffuse slowly and stay close to the ground. Because of convection, warm sources of CO_2 will diffuse better but tend to rise and accumulate near the greenhouse ridge.
5. Air movement in the greenhouse. Forced-air distribution systems effectively distribute the CO_2 but also increase infiltration air exchange slightly.
6. Photosynthetic activity. This varies with a wide variety of plant and environmental factors such as light and temperature levels.
7. Use of organic mulches. Decaying organic matter such as mulches can significantly increase CO_2 levels.
8. Irrigation. CO_2 levels tend to increase immediately following irrigation. The reason for this is not clearly understood.

These changing factors make it difficult to figure CO_2 consumption to maintain a given level. A suggested guideline, however, is that about 100 pounds of CO_2 per growing acre per hour will provide a 2,000 ppm concentration.

CO_2 Sources

Sources of CO_2 for greenhouse enrichment are either direct or indirect. Direct sources include solid and liquid forms of CO_2 and misting with carbonated water, which has only been tried experimentally. Indirect sources include CO_2 generation by burning certain fossil fuels or by the decaying of organic mulches.

Liquid CO_2 is a clean source but usually more expensive than generating CO_2 by combustion. Actual costs for liquid CO_2 vary with the amount purchased and the distance from the supplier. Approximate cost figures are \$60 to \$70 per ton for a large grower relatively close to a supplier and \$100 per ton for a smaller grower. A rule of thumb for liquid CO_2 enrichment is that one pound liquid CO_2 per square foot per year is equivalent to 1,000 ppm. Similarly 1.5 pound liquid CO_2 per square foot per year is equivalent to 1,500 ppm. At 1,500 ppm and \$100 per ton, this amounts to 7.5¢ per square foot per year and at \$60 per ton, 4.5¢ per square foot per year.

Combustion units to generate CO_2 are either (1) open flame, non-vented, within house "heater," (2) forced draft, externally located, pre-cooled, CO_2-air mixture generator, or (3) highly developed systems with pre-combustion scrubbers to remove fuel contaminants and post-combustion absorption towers to remove products of incomplete combustion (Fig. 6.E.1-3.). The small, open-flame units are currently the most popular and the least expensive. Each cubic foot of natural gas burned will generate approximately 0.12 lbs. of CO_2. A natural gas cost of \$2.50/1,000 c.f. is then equivalent to \$40 per ton of CO_2. At this cost and assuming 75 pounds of CO_2 per growing acre per hour will provide a 1,500 ppm concentration (because of increased losses from warm CO_2), the CO_2 will cost about 3.4¢ per square foot per year (not including heat value of natural gas and based on 1,000 hours/year of enrichment).

A widespread practice in Europe is to use flue gas from unlined natural gas boilers as a source of CO_2. (Boilers lined with refractory brick liners are unacceptable due to discharge of toxic gases.) Only a small portion of the flue gas is used. One part of extracted flue gas is mixed with two parts of outside air to cool and dilute it. Automatic instrumentation is sometimes used to check for the presence of carbon monoxide (CO) and other products of incomplete combustion and to shut off the system if necessary. This practice is used only in a few North American greenhouses, probably because of old refractory-lined boilers, dirty fuels, and code restrictions requiring boilers to be vented outside.

Fuels commonly burned to generate CO_2 are propane, natural gas, and kerosene (sometimes referred to as a paraffin in Europe). Care should be taken to select fuels with minimal contaminants, especially sulfur. Combustion of fuels with sulfur in them generates sulfur dioxide (SO_2), and SO_2 levels above 0.2 ppm are not recommended for greenhouse crops. Check with your local fuel supplier for the contaminant levels in your fuel supply. Maximum suggested limits for sulfur content are: propane — 10 grains per 100 cubic feet; natural gas — 3.5 grains per 100 cubic feet, and kerosene — 0.02 percent. These limits are based on CO_2 generation for maximum levels of 2,000 ppm CO_2 in the greenhouse. It should be noted that problems with natural gas contaminants may become prevalent in the future, as more artificial "natural" gas is added to gas distribution pipelines.

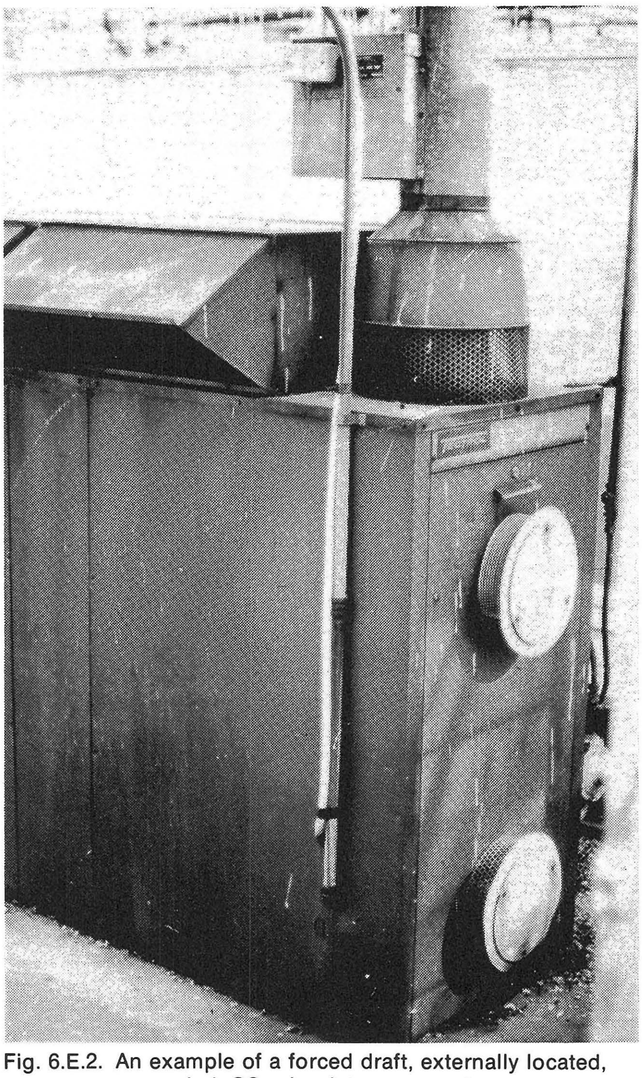


Fig. 6.E.2. An example of a forced draft, externally located, precooled, CO_2-air mixture generator.

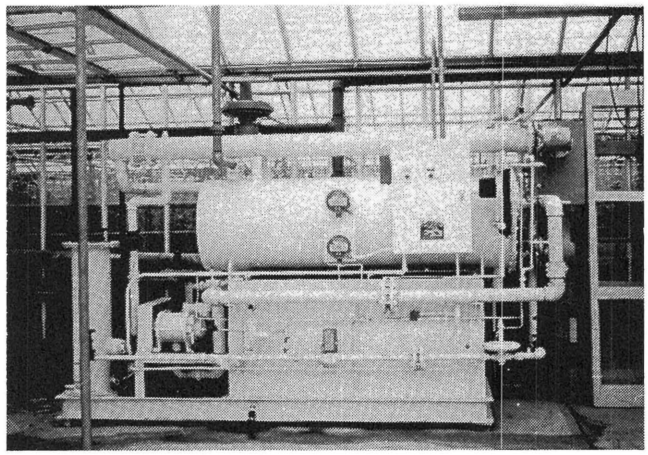


Fig. 6.E.3. An example of a CO_2 generating system with precombustion scrubber for fuel contaminants and postcombustion absorption towers to remove products of incomplete combustion.

Natural gas and propane fuels contain sulfur compounds with a distinct odor for safety purposes. Normally the amount of sulfur is too small to cause a problem. However, these compounds will settle out of propane stored in bulk tanks. Potential problems can be safely avoided, if the propane tank is not emptied below 20 percent, and the tank is thoroughly flushed before refilling at least once a year.

With any type of fuel, avoid fuel-line leaks in the greenhouse. It is also important that the burners be designed and operated to provide for complete fuel combustion. The use of in-house, open-flame CO_2 generators as the only source or a major source of *heat* in a greenhouse is risky, as these units require adequate levels of oxygen to insure complete combustion. Incomplete combustion may result in the production of harmful gases, including carbon monoxide (CO). Tomato plants will not tolerate CO levels above 500 ppm. Other products of incomplete combustion, such as ethylene, are known to cause damage to greenhouse crops.

Carbon dioxide generators used as heat sources will generate CO_2 mainly at night when heat is usually needed. Because sufficient light must be present for photosynthesis, the plants are unable to use CO_2 during the night, and excessive levels of CO_2 may build up. Tomato plants will not tolerate CO_2 levels above 10,000 ppm, for example.

Burning fuels for purposes of CO_2 enrichment releases water vapor and heat during the combustion process. High relative humidities in the greenhouse may create disease problems, and depending upon the amount of light available and the heating requirements of the greenhouse, the heat generated may be undesirable. Excessive temperatures and relative humidities are best controlled by venting which is wasteful of energy and CO_2. Table 6.E.1 shows the amounts of CO_2 and water vapor produced per quantity of fuel burned. It is calculated that the amount of water vapor added by evaporation from the plants and soil to the greenhouse air during a day will be four times that added by burning natural gas in an unvented "heater" to maintain 1,500 ppm CO_2.

Distribution

Carbon dioxide distribution systems vary with the source of CO_2. Small greenhouses are generally enriched with a centrally located, small open-flame burner. The warm CO_2 tends to diffuse readily throughout the greenhouse without circulation fans. Larger greenhouses are enriched either by placing a number of small generating units around the greenhouse or with a single large generating unit and forced-air distribution systems. Forced-air distribution systems may consist of a series of spaced mixing-type fans or fans blowing air through perforated plastic ducts or be associated with the heat distribution system. Improper distribution may cause uneven plant growth and plant damage from excessive CO_2 levels.

Liquid carbon dioxide is stored outside the greenhouse in pressurized, refrigerated containers. The liquid is vaporized in the storage chamber and then either piped around the greenhouse through plastic tubing or released into forced-air distribution systems. Semi-rigid plastic tubing is inexpensive and allows higher gas pressures and flow rates than lighter poly tubing.

TABLE 6.E.1. Water vapor and CO_2 production per quantity of fuel burned.

1

Type of gas	Approx. cu. ft. of gas burned/1,000 Btu of rated input	Products of combustion/cu. ft. of gas burned: cu. ft. H_2O	cu. ft. CO_2
Natural	1	2	1
Butane	0.3	5	4
Propane	0.4	4	3

Chart from Modine Manufacturing Co. Greenhouse Heating Engineering Manual.

The temperature of the added CO_2 affects the degree of dispersion. The warm CO_2 from combustion sources will rise to the roof unless forced down. Cool CO_2 from liquid or solid sources will drop in the greenhouse and should be introduced near the top of the plants.

CO_2 Measurements

Carbon dioxide in the greenhouse may be measured continuously or periodically. Instruments for continuous measurement, such as infrared CO_2 analyzers, are usually too expensive for commercial growers. However, a number of inexpensive ($100 to $200) instruments are capable of accurate periodic sampling. Typically, these instruments draw a measured volume of air through a sensitive absorber chemical which changes color as it reacts with the CO_2. The chemical is stored in small, disposable glass tubes. Replacement tubes cost about $1.25 each.

Because of the plant and environmental factors listed previously, the level of CO_2 in the greenhouse will vary throughout the day. If a sample is collected too soon after the generator is started, the CO_2 level may not have reached its maximum. Samples collected late in the day may indicate depressed levels due to high rates of photosynthesis. To give the most accurate estimate of average carbon dioxide levels, samples should be taken at the same time of day and preferably at 10 a.m. Avoid breathing close to the immediate sampling point, as human breath contains approximately 40,000 ppm CO_2.

Control Systems

Automatic maintenance of given concentrations of CO_2 is difficult without continuously monitoring instruments. Timers control most enrichment systems by regulating the time of burning for a combustion generator source or the release of gas from a liquid CO_2 source. By taking periodic samples manually, the grower can adjust the timer to approximate the desired level of CO_2 in the greenhouse.

Timers are normally set to start CO_2 enrichment at sunrise and stop an hour before sunset. The timers should be checked regularly to insure that a power failure has not shifted their operation off schedule. Because CO_2 enrichment is difficult with greenhouse vents open, a limit switch should be mounted at the vents to open the electrical control circuit and prevent CO_2 enrichment when vents are open.

sample calculations

Before investing in a heat conservation system, a grower should have some idea as to how effective his investment will be. A good estimate of fuel savings can usually be calculated from the information just given.

As an example, consider a grower who wants to install glass lap sealants on his greenhouse. From his fuel records, the grower knows that his fuel cost is approximately $40,000 per acre per year. Based on the information given in this handbook and the condition of his greenhouse, the grower estimates that he can save 25 percent of his fuel bill with glass lap sealants and that the sealant will cost him 40¢ per square foot of area covered, installed. The grower can follow these steps to determine the payback period for this modification:

1. Present fuel bill, $40,000/acre-year (from fuel records)
2. Projected annual savings, 25 percent (from handbook information and house condition).
3. Savings per year are $40,000 x 0.25 = $10,000/acre-year
4. Compute savings per year per square foot: $10,000/acre-year ÷ 43,560 sq. ft./acre = $0.23/sq. ft. year
5. Estimated total installed cost, $0.40/sq. ft. (from handbook or salesman information)
6. Payback time: cost/sq. ft ÷ savings/sq. ft-yr. = $0.40 sq. ft. ÷ $0.23 sq. ft-yr. = 1.7 years·

The grower can conclude that for these conditions, glass lap sealants applied to his greenhouse will pay back his investment in 1.7 years.

The grower should also be aware of the expected life of the method chosen. In this case, some glass lap sealants are guaranteed for 10 years, well beyond the payback time.

Trademark Acknowledgements

Acrylite S.D.P., TM CY/RO Industries
Aircap, TM Sealed Air Corporation
Al/Blac, TM Simtrac, Inc.
Al/Temp, TM Simtrac, Inc.
Foylon, TM Duracote Corp.
Microfoam, TM DuPont
Styrofoam, TM Dow Chemical
Tuffak-Twinwall, TM Rohm and Haas Co.
Thermopane, TM Libbey-Owens-Ford Co.
Reemay, TM DuPont

Issued in furtherance of Cooperative Extension work, acts of May 8 and June 30, 1914, in cooperation with the U.S. Department of Agriculture. Roy M. Kottman, director of The Cooperative Extension Service, The Ohio State University.

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